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OIPE IAP27 MAY 30 2006 PATENT & TRADEMARK OFFICE

Office Action Summary	Application No.	Applicant(s)
	10/717,508	GOJER, LEONARD JOSEPH
	Examiner	**Art Unit**
	Johannes P. Mondt	3663

-- The MAILING DATE of this communication appears on the cover sheet with the correspondence address --

Period for Reply

A SHORTENED STATUTORY PERIOD FOR REPLY IS SET TO EXPIRE 3 MONTH(S) OR THIRTY (30) DAYS, WHICHEVER IS LONGER, FROM THE MAILING DATE OF THIS COMMUNICATION.

- Extensions of time may be available under the provisions of 37 CFR 1.136(a). In no event, however, may a reply be timely filed after SIX (6) MONTHS from the mailing date of this communication.
- If NO period for reply is specified above, the maximum statutory period will apply and will expire SIX (6) MONTHS from the mailing date of this communication.
- Failure to reply within the set or extended period for reply will, by statute, cause the application to become ABANDONED (35 U.S.C. § 133). Any reply received by the Office later than three months after the mailing date of this communication, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

Status

1)☒ Responsive to communication(s) filed on *4/26/04*.

2a)☐ This action is **FINAL**. 2b)☒ This action is non-final.

3)☐ Since this application is in condition for allowance except for formal matters, prosecution as to the merits is closed in accordance with the practice under *Ex parte Quayle*, 1935 C.D. 11, 453 O.G. 213.

Disposition of Claims

4)☒ Claim(s) *1* is/are pending in the application.

4a) Of the above claim(s) _____ is/are withdrawn from consideration.

5)☐ Claim(s) _____ is/are allowed.

6)☒ Claim(s) *1* is/are rejected.

7)☐ Claim(s) _____ is/are objected to.

8)☐ Claim(s) _____ are subject to restriction and/or election requirement.

Application Papers

9)☒ The specification is objected to by the Examiner.

10)☐ The drawing(s) filed on _____ is/are: a)☐ accepted or b)☐ objected to by the Examiner.

Applicant may not request that any objection to the drawing(s) be held in abeyance. See 37 CFR 1.85(a).

Replacement drawing sheet(s) including the correction is required if the drawing(s) is objected to. See 37 CFR 1.121(d).

11)☐ The oath or declaration is objected to by the Examiner. Note the attached Office Action or form PTO-152.

Priority under 35 U.S.C. § 119

12)☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

a)☐ All b)☐ Some * c)☐ None of:

1.☐ Certified copies of the priority documents have been received.

2.☐ Certified copies of the priority documents have been received in Application No. _____.

3.☐ Copies of the certified copies of the priority documents have been received in this National Stage application from the International Bureau (PCT Rule 17.2(a)).

* See the attached detailed Office action for a list of the certified copies not received.

Attachment(s)

1) ☒ Notice of References Cited (PTO-892)

2) ☐ Notice of Draftsperson's Patent Drawing Review (PTO-948)

3) ☐ Information Disclosure Statement(s) (PTO-1449 or PTO/SB/08) Paper No(s)/Mail Date _____.

4) ☐ Interview Summary (PTO-413) Paper No(s)/Mail Date. _____ .

5) ☐ Notice of Informal Patent Application (PTO-152)

6) ☐ Other: _____.

DETAILED ACTION

This office action is in response to the filing of the application.

Drawings

The subject matter of this application admits of illustration by a drawing to facilitate understanding of the invention. No drawings have been found in the application. Applicant is required to furnish a drawing under 37 CFR 1.81(c). No new matter may be introduced in the required drawing. Each drawing sheet submitted after the filing date of an application must be labeled in the top margin as either "Replacement Sheet" or "New Sheet" pursuant to 37 CFR 1.121(d).

Specification

Applicant is reminded of the proper content of an abstract of the disclosure.

A patent abstract is a concise statement of the technical disclosure of the patent and should include that which is new in the art to which the invention pertains. If the patent is of a basic nature, the entire technical disclosure may be new in the art, and the abstract should be directed to the entire disclosure. If the patent is in the nature of an improvement in an old apparatus, process, product, or composition, the abstract should include the technical disclosure of the improvement. In certain patents, particularly those for compounds and compositions, wherein the process for making and/or the use thereof are not obvious, the abstract should set forth a process for making and/or use thereof. If the new technical disclosure involves modifications or alternatives, the abstract should mention by way of example the preferred modification or alternative.

The abstract should not refer to purported merits or speculative applications of the invention and should not compare the invention with the prior art.

Where applicable, the abstract should include the following:
(1) if a machine or apparatus, its organization and operation;
(2) if an article, its method of making;
(3) if a chemical compound, its identity and use;
(4) if a mixture, its ingredients;
(5) if a process, the steps.

Extensive mechanical and design details of apparatus should not be given.

- The abstract of the disclosure is objected to because applicant's abstract is neither concise nor comprehensible, while referring to purported merits and speculative applications. Correction is required. See MPEP § 608.01(b).
- Applicant is reminded of the proper language and format for an abstract of the disclosure.

The abstract should be in narrative form and generally limited to a single paragraph on a separate sheet within the range of 50 to 150 words. It is important that the abstract not exceed 150 words in length since the space provided for the abstract on the computer tape used by the printer is limited. The form and legal phraseology often used in patent claims, such as "means" and "said," should be avoided. The abstract should describe the disclosure sufficiently to assist readers in deciding whether there is a need for consulting the full patent text for details.The language should be clear and concise and should not repeat information given in the title. It should avoid using phrases which can be implied, such as, "The disclosure concerns," "The disclosure defined by this invention," "The disclosure describes," etc., including the phrase "It describes", "The invention works", etc., used in applicant's abstract.

The following guidelines illustrate the preferred layout for the specification of a utility application. These guidelines are suggested for the applicant's use.

Arrangement of the Specification

As provided in 37 CFR 1.77(b), the specification of a utility application should include the following sections in order. Each of the lettered items should appear in upper case, without underlining or bold type, as a section heading. If no text follows the section heading, the phrase "Not Applicable" should follow the section heading:

(a) TITLE OF THE INVENTION.
(b) CROSS-REFERENCE TO RELATED APPLICATIONS.
(c) STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT.

(d) THE NAMES OF THE PARTIES TO A JOINT RESEARCH AGREEMENT
(e) INCORPORATION-BY-REFERENCE OF MATERIAL SUBMITTED ON A COMPACT DISC (See 37 CFR 1.52(e)(5) and MPEP 608.05. Computer program listings (37 CFR 1.96(c)), "Sequence Listings" (37 CFR 1.821(c)), and tables having more than 50 pages of text are permitted to be submitted on compact discs.) or
REFERENCE TO A "MICROFICHE APPENDIX" (See MPEP § 608.05(a). "Microfiche Appendices" were accepted by the Office until March 1, 2001.)
(f) BACKGROUND OF THE INVENTION.
(1) Field of the Invention.
(2) Description of Related Art including information disclosed under 37 CFR 1.97 and 1.98.
(g) BRIEF SUMMARY OF THE INVENTION.
(h) BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING(S).
(i) DETAILED DESCRIPTION OF THE INVENTION.
(j) CLAIM OR CLAIMS (commencing on a separate sheet).
(k) ABSTRACT OF THE DISCLOSURE (commencing on a separate sheet).
(l) SEQUENCE LISTING (See MPEP § 2424 and 37 CFR 1.821-1.825. A "Sequence Listing" is required on paper if the application discloses a nucleotide or amino acid sequence as defined in 37 CFR 1.821(a) and if the required "Sequence Listing" is not submitted as an electronic document on compact disc).

Content of Specification

(a) Title of the Invention: See 37 CFR 1.72(a) and MPEP § 606. The title of the invention should be placed at the top of the first page of the specification unless the title is provided in an application data sheet. The title of the invention should be brief but technically accurate and descriptive, preferably from two to seven words may not contain more than 500 characters.

(b) Cross-References to Related Applications: See 37 CFR 1.78 and MPEP § 201.11.

(c) Statement Regarding Federally Sponsored Research and Development: See MPEP § 310.

(d) The Names Of The Parties To A Joint Research Agreement: See 37 CFR 1.71(g).

(e) Incorporation-By-Reference Of Material Submitted On a Compact Disc: The specification is required to include an incorporation-by-reference of electronic documents that are to become part of the permanent United States Patent and Trademark Office records in the file of a patent application. See 37 CFR 1.52(e) and MPEP § 608.05. Computer program listings (37 CFR 1.96(c)), "Sequence Listings" (37 CFR 1.821(c)), and tables having more than 50 pages of text were permitted as electronic documents on compact discs beginning on September 8, 2000.

Or alternatively, Reference to a "Microfiche Appendix": See MPEP § 608.05(a). "Microfiche Appendices" were accepted by the Office until March 1, 2001.

(f) Background of the Invention: See MPEP § 608.01(c). The specification should set forth the Background of the Invention in two parts:

(1) Field of the Invention: A statement of the field of art to which the invention pertains. This statement may include a paraphrasing of the applicable U.S. patent classification definitions of the subject matter of the claimed invention. This item may also be titled "Technical Field."

(2) Description of the Related Art including information disclosed under 37 CFR 1.97 and 37 CFR 1.98: A description of the related art known to the applicant and including, if applicable, references to specific related art and problems involved in the prior art which are solved by the applicant's invention. This item may also be titled "Background Art."

(g) Brief Summary of the Invention: See MPEP § 608.01(d). A brief summary or general statement of the invention as set forth in 37 CFR 1.73. The summary is separate and distinct from the abstract and is directed toward the invention rather than the disclosure as a whole. The summary may point

out the advantages of the invention or how it solves problems previously existent in the prior art (and preferably indicated in the Background of the Invention). In chemical cases it should point out in general terms the utility of the invention. If possible, the nature and gist of the invention or the inventive concept should be set forth. Objects of the invention should be treated briefly and only to the extent that they contribute to an understanding of the invention.

(h) Brief Description of the Several Views of the Drawing(s): See MPEP § 608.01(f). A reference to and brief description of the drawing(s) as set forth in 37 CFR 1.74.

(i) Detailed Description of the Invention: See MPEP § 608.01(g). A description of the preferred embodiment(s) of the invention as required in 37 CFR 1.71. The description should be as short and specific as is necessary to describe the invention adequately and accurately. Where elements or groups of elements, compounds, and processes, which are conventional and generally widely known in the field of the invention described and their exact nature or type is not necessary for an understanding and use of the invention by a person skilled in the art, they should not be described in detail. However, where particularly complicated subject matter is involved or where the elements, compounds, or processes may not be commonly or widely known in the field, the specification should refer to another patent or readily available publication which adequately describes the subject matter.

(j) Claim or Claims: See 37 CFR 1.75 and MPEP § 608.01(m). The claim or claims must commence on separate sheet or electronic page (37 CFR 1.52(b)(3)). Where a claim sets forth a plurality of elements or steps, each element or step of the claim should be separated by a line indentation. There may be plural indentations to further segregate subcombinations or related steps. See 37 CFR 1.75 and MPEP § 608.01(i)-(p).

(k) Abstract of the Disclosure: See MPEP § 608.01(f). A brief narrative of the disclosure as a whole in a single paragraph of 150 words or less commencing on a separate sheet following the claims. In an international application which has entered the national stage (37 CFR 1.491(b)), the applicant need not submit an abstract commencing on a separate sheet if an abstract was published with the international application under PCT Article 21. The abstract that appears on the cover page of the pamphlet published by the International Bureau (IB) of the World Intellectual Property Organization (WIPO) is the abstract that will be used by the USPTO. See MPEP § 1893.03(e).

(l) Sequence Listing. See 37 CFR 1.821-1.825 and MPEP §§ 2421-2431. The requirement for a sequence listing applies to all sequences disclosed in a given application, whether the sequences are claimed or not. See MPEP § 2421.02.

The specification shall contain a written description of the invention, and of the manner and process of making and using it, in such full, clear, concise, and exact terms as to enable any person skilled in the art to which it pertains, or with which it is most nearly connected, to make and use the same and shall set forth the best mode contemplated by the inventor of carrying out his invention.

1. ***The Specification is objected to*** because the written description is both (a) insufficient in its description of the claimed fusion reactor and (b) fails to provide enablement for the claimed invention.

A major contribution to both currents and fields originates from the motion of both ions and electrons in the plasma in response to, and yet also contributing to, the electromagnetic fields. The stability properties of the

configuration of electric and magnetic fields with the plasma have not been discussed, yet stability is of major concern for toroidal pinch type configurations as evidenced for instance by Alper, Physics of Fluids B2(6), June 1990, pages 1338-1341); nor has the net yield of energy, i.e., retrievable fusion energy minus energy required to reach and maintain the necessary plasma density and ion temperature, been described, although applicant includes a major limitation in that regard ("fusion reactor", final sentence). Therefore, from the Specification it is not clear whether the ion temperature can reach the threshold for thermonuclear fusion (depending on the specific nuclei participating in the nuclear fusion reaction, but at least several tens of millions degrees (C or K), see L. A. Artsimovich, "Controlled Thermonuclear Reactions", Gordon & Breach Science Publishers, New York, English Edition 1964, pages 1-9; see for instance Figure 7 illustrating the ratio of energy released by thermonuclear reactions to that lost by one source of loss, i.e., Bremsstrahlung losses, i.e., radiation and, consequently heat losses due to deceleration of charge carriers resulting from their interaction at high relative velocities; other heat sinks are just as important, e.g., plasma-wall interaction and the accumulation of helium ash), nor is it clear from the Specification whether Lawson's criterion for achieving a net energy output from a thermonuclear reactor is met (see, e.g., J.D. Lawson, Proc. Phys. Soc. B70, 6-10 (1957)). Moreover, aforementioned threshold for ion temperature and Lawson's criterion should be achieved *simultaneously*.

A written description and the provision of enablement of the claimed invention (*ad (a) above*) is lacking at least for the above reasons.

With regard to enablement (ad (b) above) it is further noted that the achievement of a fusion reactor has been an as yet unachieved objective of intensive research and development worldwide over the last half a century, and thus far this effort has still not met the objective exactly because of the problems of stability and heating / heat loss described above despite an increased consensus of its urgency; see, for instance "International Research Co-operation in the Field of Controlled Thermonuclear Fusion, 25th Report covering 2002, by the Federal Office for Education and Science; see also the position statement of the IEEE-USA Board of Directors (June 1999), entitled "Fusion Energy Research and Development"). In view of the nature of the invention, i.e., a fusion reactor, generally recognized as a major yet unachieved, milestone to solve the world's energy resource problems, and given the state of the prior art and the level of ordinary skill in the art of thermonuclear fusion at present as not being able to satisfy the aforementioned necessary conditions for ion temperature and density, given also the level of predictability in the art, which must need be described as poor from an *a priori*, i.e., experimentally untested, point of departure as a history of repeated setbacks in the worldwide fusion research and development effort has demonstrated, and, finally, given the lack of an adequate written description tantamount to zero direction by the inventor and

no working examples being detailed in any reasonable sense of the word, there is no doubt that undue experimentation is required to practice the invention. In conclusion, with reference to *MPEP 2164.01(a)* the claimed invention is not enabled by the Specification. Finally, the showing of a credible asserted utility or well-established utility of the invention is clearly failing in light the above-noted lack of enablement, credibility being absent in view of the lack of an adequate description and of enablement of the claimed invention in conjunction with its nature, the state and level of predictability of the art and the need for undue experimentation as explained overleaf.

Claim Objections

2. The claim of inventor is objected to because any sheet including a claim or portion of a claim may not contain any other parts of the application or other material (MPEP 608.01(m)).
3. The claim is objected to because of the following informalities: the wording "thi" on line 1 should be replaced by "the"; the wording "it's" on line 1 should be replaced by "its"; and the wording "sin wave" on lines 6-7, 9-10, should be replaced by "sine wave". Appropriate correction is required.

Claim Rejections - 35 USC § 112

The following is a quotation of the first paragraph of 35 U.S.C. 112:

The specification shall contain a written description of the invention, and of the manner and process of making and using it, in such full, clear, concise, and exact terms as to enable any person skilled in the art to which it pertains, or with which it is most nearly connected, to make and use the same and shall set forth the best mode contemplated by the inventor of carrying out his invention.

4. ***The claim by inventor is rejected* under 35 U.S.C. 112, first paragraph**, as failing to comply with the *written description* requirement. The claim contains subject matter not described in the specification in such a way as to reasonably convey to one skilled in the relevant art that the inventor, at the time the application was filed, had possession of the claimed invention. See objection to the Specification under section 1 above in this office action incorporated herewith.

5. ***The claim by inventor is furthermore rejected under 35 U.S.C. 112, first paragraph***, as failing to comply with the enablement requirement. The claim contains subject matter not described in the specification in such a way as to enable one skilled in the art to which it pertains, or with which it is most nearly connected, to make and/or use the invention. See objection to the Specification under section 1 above in this office action incorporated herewith.

The following is a quotation of the second paragraph of 35 U.S.C. 112:

> The specification shall conclude with one or more claims particularly pointing out and distinctly claiming the subject matter which the applicant regards as his invention.

1. ***The claim by inventor is rejected under 35 U.S.C. 112, second paragraph,*** as being indefinite for failing to particularly point out and distinctly claim the subject matter which applicant regards as the invention. In particular, "wave-form" (line 1) is indefinite, not being defined in the claim, nor has "wave-form" been defined in the Specification. "Wave-form" necessarily has to be defined as an attribute of a physical parameter, such as current, voltage, magnetic field, electric field, or

electromagnetic field, for instance. Absent the physical parameter of which said "wave-form" is an attribute, "wave-form" is indefinite. Neither does applicant explain how a wave-form can be "passing through" wires; in any reasonable interpretation, "wave-form" merely is a functional form of the time dependence of a physical quantity. That said physical quantity can be claimed to pass through wires is a different matter altogether.

2. A second, independent reason for indefiniteness is that the wave-form is claimed to be "the invention of the inventor" (lines 1-2), all other features being "public domain knowledge" (lines 2-5), whereas subsequently in the same claim the "topology (of the wires) is the factor that produces a successful design of the fusion reactor"; however, in any reasonable interpretation of "wave-form" and "topology" the former pertains to the time dependence and the latter to the spatial dependence, implying a bewildering contradiction in what is claimed to be the novel feature of the claimed invention.
3. The claim by inventor recites the limitation ""the wave-form" (in line 1). There is insufficient antecedent basis for this limitation in the claim.
4. The claim by inventor recites the limitation "the intention of the wave-form" (in lines 4-5). There is insufficient antecedent basis for this limitation in the claim.
5. The claim by inventor recites the limitation ""the patent" (in line 3). There is insufficient antecedent basis for this limitation in the claim.

6. The claim by inventor recites the limitation ""the desired field" (in line 11). There is insufficient antecedent basis for this limitation in the claim.
7. The claim by inventor recites the limitation ""the topology of the wires" (in line 20). There is insufficient antecedent basis for this limitation in the claim.

Claim Rejections - 35 USC § 101

35 U.S.C. 101 reads as follows:

> Whoever invents or discovers any new and useful process, machine, manufacture, or composition of matter, or any new and useful improvement thereof, may obtain a patent therefor, subject to the conditions and requirements of this title.

1. The claim by inventor is rejected under 35 U.S.C. 101 because the claimed invention is not supported by either a specific and substantial asserted utility or a well established utility.

The claimed invention is not supported by the Specification, which fails to show neither a credible asserted utility nor a well established utility, with reference to the objection to the Specification under section 1 above.

Said claim also is rejected under 35 U.S.C. 112, first paragraph. Specifically, since the claimed invention is not supported by either a specific and substantial asserted utility or a well established utility for the reasons set forth above under section 1 on objections to the Specification, herewith incorporated, one skilled in the art clearly would not know how to use the claimed invention.

Claim Rejections - 35 USC § 102

The following is a quotation of the appropriate paragraphs of 35 U.S.C. 102 that form the basis for the rejections under this section made in this Office action:

A person shall be entitled to a patent unless –

(b) the invention was patented or described in a printed publication in this or a foreign country or in public use or on sale in this country, more than one year prior to the date of application for patent in the United States.

2. ***The claim is rejected under 35 U.S.C. 102(b)*** as being anticipated by Ohkawa (4,560,528) henceforth abbreviated by Ohkawa_1, as well as by Ohkawa (4,543,231), the latter henceforth abbreviated by Ohkawa_2. These rejections are provided subject to the noted indefiniteness under 35 USC 112, second paragraph, and lack of enablement of the claimed fusion reactor, and merely serves to show that the apparatus to the extent as claimed with regard to its definite attributes is in the prior art.

Ohkawa_1 teaches an apparatus comprising a magnetic bottle (abstract, first sentence, "magnetic well" meets the claim limitation "magnetic bottle") while the "wave-form", whether of external magnetic fields, currents in the wires inherently needed to produce said external magnetic fields, electric fields, or electromagnetic fields, being analytical in the spatial domain of the confined plasma, can inherently be accurately approximated by a Fourier decomposition in sine waves on account of the completeness of the set of harmonic functions in the space of analytical functions. The pinch effect, i.e., confinement through the motion of charge carriers in the self-field of the plasma, is indeed operative (column 11, lines 32-45) on the hydrogen ions (column 10, line 21). The toroidal magnetic field coils 58 (column 12, lines 28-48) of Ohkawa_1 meet the claimed "coils of electromagnets". The physical dimensions are inherently variable, i.e., they can be varied in any design, if only because the laws of electromagnetic fields and the response of ions and electrons yield relations between

fields and particle quantities such as density, temperature, pressure, heat tensor, etc., that are characterized by continuous functions. The topology of the wires is not defined, being without antecedent basis in the claim, and hence the limitation "the topology of the wires" does not carry patentable weight. The limitation "the only limiting criteria being how much energy does the designer want to produce" and the limitation on "successful design of a fusion reactor" are not enabled, as explained under the objection to the specification and the rejection under 35 USC 112, first paragraph, and constitute a major difficulty in patentability subject to the use of the apparatus as claimed.

Ohkawa_2 teaches an apparatus comprising a magnetic bottle (abstract, first sentence, "magnetic well" meets the claim limitation "magnetic bottle") while the "wave-form", whether of external magnetic fields, currents in the wires inherently needed to produce said external magnetic fields, electric fields, or electromagnetic fields, being analytical in the spatial domain of the confined plasma, can inherently be accurately approximated by a Fourier decomposition in sine waves on account of the completeness of the set of harmonic functions in the space of analytical functions. The pinch effect, i.e., confinement through the motion of charge carriers in the self-field of the plasma, is indeed operative (column 7, lines 1-15) on the hydrogen ions (column 7, line 62). The toroidal magnetic field coils 58 (column 10, lines 7-18) of Ohkawa_2 meet the claimed "coils of electromagnets". The physical dimensions are inherently variable, i.e., they can be varied in any design, if only because the laws of electromagnetic fields and the response of ions and electrons yield relations between fields and particle

quantities such as density, temperature, pressure, heat tensor, etc., that are characterized by continuous functions. The topology of the wires is not defined, being without antecedent basis in the claim, and hence the limitation "the topology of the wires" does not carry patentable weight. The limitation "the only limiting criteria being how much energy does the designer want to produce" and the limitation on "successful design of a fusion reactor" are not enabled, as explained under the objection to the specification and the rejection under 35 USC 112, first paragraph, and constitute a major difficulty in patentability subject to the use of the apparatus as claimed.

Conclusion

Any inquiry concerning this communication or earlier communications from the examiner should be directed to Johannes P. Mondt whose telephone number is 571-272-1919. The examiner can normally be reached on 8:00 - 18:00.

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Jack W. Keith can be reached on 571-272-6878. The fax phone number for the organization where this application or proceeding is assigned is 571-273-8300.

Information regarding the status of an application may be obtained from the Patent Application Information Retrieval (PAIR) system. Status information for published applications may be obtained from either Private PAIR or Public PAIR. Status information for unpublished applications is available through Private PAIR only. For more information about the PAIR system, see http://pair-direct.uspto.gov. Should you have questions on access to the Private PAIR system, contact the Electronic Business Center (EBC) at 866-217-9197 (toll-free).

JPM
May 16, 2006

Patent Examiner:

Johannes Mondt (Art Unit: 3663)

Notice of References Cited	Application/Control No. 10/717,508	Applicant(s)/Patent Under Reexamination GOJER, LEONARD JOSEPH	
	Examiner Johannes P. Mondt	Art Unit 3663	Page 1 of 2

U.S. PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Name	Classification
*	A	US-4,560,528	12-1985	Ohkawa, Tihiro	376/121
*	B	US-4,543,231	09-1985	Ohkawa, Tihiro	376/133
	C	US-			
	D	US-			
	E	US-			
	F	US-			
	G	US-			
	H	US-			
	I	US-			
	J	US-			
	K	US-			
	L	US-			
	M	US-			

FOREIGN PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Country	Name	Classification
	N					
	O					
	P					
	Q					
	R					
	S					
	T					

NON-PATENT DOCUMENTS

*		Include as applicable: Author, Title Date, Publisher, Edition or Volume, Pertinent Pages)
	U	Alper, B., Phys. of Fluids B2 (6), June 1990, pages 1338-1341 (AIP)
	V	Lawson, J.D., Proc. Phys. Soc. B70, pages 1-6
	W	L. A. Artsimovich, "Controlled Thermonuclear Reactions", Gordon & Breach Science Publishers, New York 1964 (first English Edition), pages 1-9
	X	"International Research Co-operation in the Field of Controlled Thermonuclear Fusion, 25th Report covering 2002", Federal Office for Education and Science, Switserland

*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.

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U.S. PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Name	Classification
	A	US-			
	B	US-			
	C	US-			
	D	US-			
	E	US-			
	F	US-			
	G	US-			
	H	US-			
	I	US-			
	J	US-			
	K	US-			
	L	US-			
	M	US-			

FOREIGN PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Country	Name	Classification
	N					
	O					
	P					
	Q					
	R					
	S					
	T					

NON-PATENT DOCUMENTS

*		Include as applicable: Author, Title Date, Publisher, Edition or Volume, Pertinent Pages)
	U	"IEEE-USA Position Statement on Fusion Energy Research and Development", approved by the IEEE-USA Board of Directors (June 1999).
	V	
	W	
	X	

*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.

item U an PTo 8?92

A review of results from the HBTX reversed field pinch*

B. Alper
UKAEA/Euratom Fusion Association, Culham Laboratory, Abingdon, Oxfordshire OX14 3DB, United Kingdom

(Received 13 November 1989; accepted 21 February 1990)

The series of experiments carried out in recent years on the HBTX reversed field pinch [Plasma Phys. Controlled Fusion 30, 843 (1988)] have highlighted the importance of minimizing the flux that penetrates the plasma–wall boundary. This flux penetration, whether from equilibrium field errors, the presence of limiters, or plasma magnetic activity from the growth of thin shell modes, leads to an increase in the loop voltage. The magnitude of this increase can be understood in terms of magnetic helicity balance. Feedback stabilization of the $(m,n) = (1,2)$ thin shell mode has been successfully demonstrated, though with little effect on global plasma properties. A new design is being developed for HBTX aimed at minimizing the flux that can penetrate the first wall.

I. INTRODUCTION

Throughout the 1980s experiments have been carried out at Culham on the HBTX device[1–3] (major radius = 0.8 m, minor radius = 0.26 m) to study the physics of reversed field pinch (RFP) plasmas. This device has gone through a series of modifications, first with a thick, conducting shell (wall time constant for vertical field penetration, $\tau_w = 80$ msec) in HBTX1A[1] and HBTX1B[2] and subsequently with thin resistive shells in HBTX1C[3] ($\tau_w = 0.5$ and 5.5 msec).

In the thick shell experiments, the primary aim in these modifications was to reduce the equilibrium field errors with reductions in toroidal field ripple, reductions in field errors at ports and shell gaps, and centering of the plasma with a dc vertical field. The presence of fixed limiters in HBTX1B was also identified as a source of field errors and experiments were performed before and after their removal. With each reduction in field error the confinement of the RFP plasma improved. This is discussed further in Sec. II.

In the thin shell experiments[3,4] the aim was to study the stability of RFP plasmas with a resistive wall and to exploit the potential of feedback techniques afforded by the short field penetration times of the shell. These experiments are discussed in Sec. III.

As a final phase to the HBTX program, a new first wall and smooth close-fitting shell design is being developed[5] to optimize the confinement of RFP plasmas. The thinking behind this approach is presented in Sec. IV.

II. EXPERIMENTS WITH A THICK SHELL

In Fig. 1, the measured loop voltage is plotted for a variety of conditions in HBTX1A and HBTX1B, which were operated with thick shells. The parameter plotted on the horizontal axis, the displacement, represents the maximum penetration of field errors into the RFP plasma beyond the vacuum vessel. It includes contributions not only from field ripple and plasma displacements with vertical magnetic fields (B_v) of varying strength, but also from limiters and other obstructions inserted into the plasma volume. Assuming toroidal symmetry, the displacement can be linearly related either to an equivalent scrape-off volume or to the total flux penetrating the plasma–wall boundary. The data were collected at similar plasma currents ($I_\varphi = 200 \pm 50$ kA) and have similar values of central electron temperature ($T_e = 300 \pm 100$ eV). The Spitzer loop voltage, calculated using helicity balance,[6] is 12 ± 5 V for all cases apart from the "rail limiter" data, where it is ~ 25 V. The measured loop voltage is thus observed to be greater than the Spitzer value in all cases. It also appears to be linearly related to the magnitude of the field error.

The poloidal beta (β_θ) is almost constant in these data.[2] Hence the energy confinement time (τ_E) is inversely related to the loop voltage (V_φ) and to the magnitude of the field error ($\tau_E \propto \beta_\theta I_\varphi / V_\varphi$).

Models[7,8] based on the conservation of magnetic helicity were developed to account for the additional, or "non-Spitzer" component (ΔV_φ) in the measured loop voltage on HBTX. These models suggest that the observed loop voltage can be represented in the form

$$V_\varphi = \Delta V_\varphi + I_\varphi \cdot \Omega_c, \tag{1}$$

where Ω_c is the classical or Spitzer resistance. The enhanced helicity dissipation that contributes to ΔV_φ occurs either in the edge plasma volume[7] or at an electrostatic boundary sheath[8] where the flux intercepts the first wall. In the sheath model the non-Spitzer component of loop voltage follows directly from helicity balance and is given by

$$\Delta V_\varphi = \int_{\text{wall}} \frac{\chi \mathbf{B} \cdot d\mathbf{s}}{\Phi}, \tag{2}$$

where χ is the difference in potential between the point of entry and exit of a field line at the plasma–wall boundary and Φ is the toroidal flux. The value of χ, using plasma sheath theory, can be related to the local value of T_e.

These models successfully predicted the fall in loop voltage with the removal of fixed limiters from HBTX1B.[2]

*Paper 3I4, Bull. Am. Phys. Soc. 34, 1960 (1989).

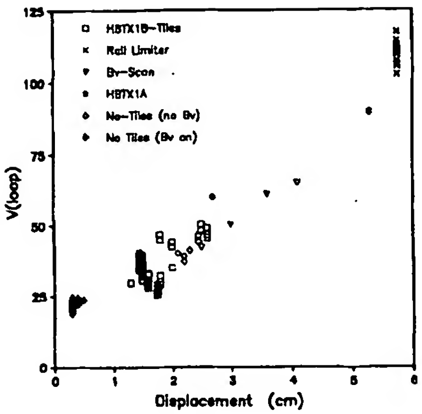

FIG. 1. The measured loop voltage plotted as a function of plasma displacement resulting from field errors or limiter insertion for various operating conditions of HBTX1A and HBTX1B.

For centered plasmas the value of ΔV_φ fell from ~ 20 V before limiter removal to ~ 10 V after removal. The value of 10 V, after the removal of limiters, is believed to be made up of contributions, partly from residual field errors at ports and shell gaps, partly from the bellows structure of the first wall, and partly from flux penetration by plasma generated radial field fluctuations. This aspect is discussed further in Sec. IV.

The helicity balance models combined with calculations of Spitzer resistivity provide a reasonable account of the loop voltage for all RFP operating conditions of HBTX with a thick conducting shell.

Nonclassical contributions by kinetic effects,[9,10] based on the concept of momentum transport by long mean-free-path (collisionless) electrons, may also be important. Hot electrons (comparable to central electron temperatures) have been observed in the HBTX edge plasma flowing in the direction of the local magnetic field and a power flux asymmetry in the electron-to-ion drift directions of $\sim 3:1$ is observed in the plasma edge region.[11]

Ions are heated more rapidly and to temperatures higher than can be explained by equipartition with the electrons. On HBTX, the ratio of ion-to-electron temperature increases with ΔV_φ. To explain these effects a model has been developed that attributes the power associated with $\Delta V_\varphi \cdot I_\varphi$ to ion heating.[12]

III. EXPERIMENTS WITH A THIN CONDUCTING SHELL

A. Plasma stability

A thin (resistive) conducting shell was installed in HBTX1C in order to investigate the stability and confinement properties of RFP plasmas whose duration exceeds the time constant of the shell. The shell (time constant $\tau_w = 0.5$ msec) was installed around the same bellows vacuum vessel as HBTX1B and at a similar distance from the plasma surface (1.15 times the minor radius a). Magnetohydrodynamic (MHD) stability calculations[13–15] pointed to the growth on the shell time scale of unstable ($m = 1$) modes that would mode lock to the wall. On-axis or internally resonant modes were predicted to dominate at low values of the pinch parameter (Θ) and externally nonresonant modes [the $(m,n) = (1,2)$, in particular] would dominate at high Θ (see below). All these features were observed in the data of HBTX1C.[3] Typically, the normalized growth rate of these modes was $\gamma\tau_w = 0.3 \pm 0.1$. They tended to have similar growth rates, suggesting the possibility of nonlinear coupling between the modes. The plasma terminated in < 10 shell times (i.e., pulse lengths were limited to < 5 msec).

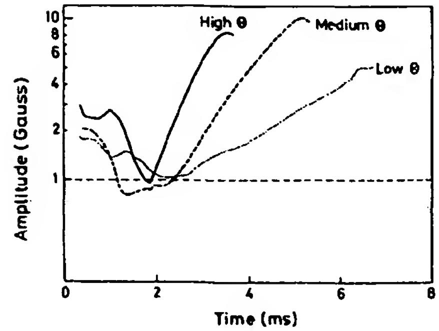

FIG. 2. Amplitude of the $(m,n) = (1,2)$ external kink mode measured outside the secondary shell for three values of (Θ): 1.6 (low), 1.9 (medium), and 2.2 (high).

Large radial fields, up to 50 G, were observed outside the windings system (at a radius of $1.6a$). Subsequent analysis showed a strong correlation between the growth of the $(m,n) = (1,2)$ mode and plasma duration. These studies prompted us to install a secondary shell of 0.5 mm of copper ($\tau_w = 5.5$ msec) at this position in order to suppress the growth of the (1,2) mode, in particular. Linear MHD calculations show that since this shell is far from the plasma surface it would preferentially suppress the growth of long-wavelength, low-n modes. It was hoped that nonlinear coupling between the modes would suppress the growth of all n modes. Experimentally, this was largely borne out. Pulse lengths doubled to ~ 10 msec, the loop voltage fell (see Sec. III C) and the growth rate of all dominant $m = 1$ modes fell[4] by a factor of > 2.

Figure 2 illustrates the dependence on Θ of the growth in amplitude of the $(m,n) = (1,2)$ external kink mode,[16] as detected by helical coils outside the secondary shell. As predicted by linear MHD theory the growth rate of this mode does indeed increase with Θ, with termination occurring when the amplitude is ~ 10 G at the secondary shell (corresponding to ~ 50 G at the plasma surface).

B. Feedback stabilization

Feedback control of the plasma horizontal position was implemented using semiconductor switches, gate turn-off thyristors, to alter the way current is shared by the parallel-connected field windings.[17] With the switches activated, the plasma is given a horizontal velocity in the desired direction of 1 mm/msec. Implementation of this

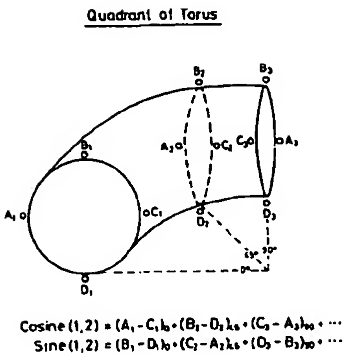

FIG. 3. Schematic drawing illustrating how the $(m,n) = (1,2)$ mode detection signal is composed of the sum and difference of poloidal field coils $(A_1,...,D_8)$.

system allowed control of the horizontal displacement of the flux surface at the wall to within ± 1 mm, compared to ± 3 mm for the best achieved passively.

This circuitry was adapted to drive currents in two helically wound coils outside the secondary shell in order to control the growth of the $(m,n) = (1,2)$ external kink mode.[4] The amplitude of this mode was detected by arrays of pairs of pickup coils that measure the difference in poloidal field between opposite pairs of coils just outside the vacuum vessel (see Fig. 3). The signal amplitude is derived from the sum of signals from eight nearly equally spaced toroidal locations. Two such signals labeled sine and cosine, 90° out of phase, are generated. When the sine/cosine signals exceed a preset value (of ~ 18 G) current in one of the helical coils of the correct phase and polarity is activated to suppress its growth. The strength of this signal is ~ 10 G at the pickup coils and ~ 7 G on axis. [As discussed in Sec. III A the $(m,n) = (1,2)$ mode grows on average to ~ 50 G at the pickup coils at termination.] Figure 4 shows the sine/cosine signals when the feedback is activated. The bars and arrows show the time and polarity of the feedback signals. The amplitude of this mode is

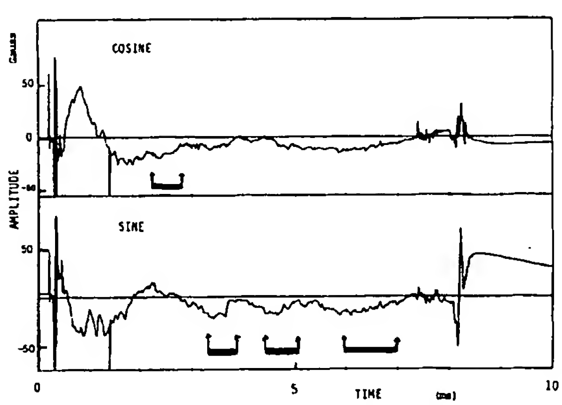

FIG. 4. Example of the effect of feedback on both phases of the $(m,n) = (1,2)$ mode. The bars and arrows depict, respectively, the time when activated and the sign of the feedback signal.

suppressed to <20 G throughout the discharge. However, although the amplitude of this mode with feedback is on average $<50\%$ of its final value without feedback, no improvement in global plasma confinement was detected. A more detailed study of the effect of this feedback on the growth of all $m = 1$ modes is in progress. MHD considerations suggest that a greater improvement in plasma stability would arise from the suppression of the growth of the internal "dynamo" modes ($n = -5$ to -7). Although from our experience this seems technically possible, it was not practicable to implement on the existing HBTX1C configuration.

C. Loop voltage studies

In thin shell operation, a typical value of the loop voltage to sustain a constant current was ~ 65 V, of which ~ 15 V can be accounted for classically. This implies a non-Spitzer contribution ΔV_φ of about 50 V. After installation of the secondary shell, the corresponding values were ~ 50 V applied, of which ~ 10 V is classical, which implies a value of ~ 40 V for ΔV_φ. It is nontrivial to test whether the helicity balance models can account for these values of ΔV_φ. Considering Eq. (2), to calculate the magnitude of ΔV_φ requires sufficient information to carry out the flux integral over the whole first wall. With equilibrium field errors or obstacles in the plasma volume this is straightforward. To carry out the corresponding integral when the flux penetration is from unstable magnetic modes requires either complete coverage of the first wall with radial-field search coils or a complete analysis of the growth of modes for all m,n values. As an approximation to the latter, discharges, both before and after installation of the secondary shell, were selected that had clear $m = 1$ dominant mode activity. Using these $m = 1$ mode amplitudes, the integral in Eq. (2) was performed[18] at one instant during the current flat top. Values of ΔV_φ obtained were 49 V for thin shell only operation and 32 V for secondary shell operation—in broad agreement with the values quoted above.

An analysis of the time dependence of ΔV_φ during a discharge was carried out for a set of discharges during operation with the secondary shell. The value of this non-Spitzer component was found to rise from 35 V at 2.5 msec into the discharge to 50 V at 4.5 msec, i.e., a growth rate of ~ 7.5 V/msec. (In thick shell operation the data were consistent with a constant value of ΔV_φ.) This growth in ΔV_φ is expected from the growth of thin shell modes through the discharge and the consequent increase of flux penetrating the first wall with time. It may also provide the reason for early termination of discharges as the applied loop voltage rapidly becomes inadequate to sustain the current and maintain reversal.

IV. ADVANCED FIRST WALL DESIGN

A new assembly structure[5] is being developed for HBTX with the primary aim of minimizing the value of ΔV_φ. To do this, the intention is to have a smooth conducting shell as close to the plasma surface as possible. By

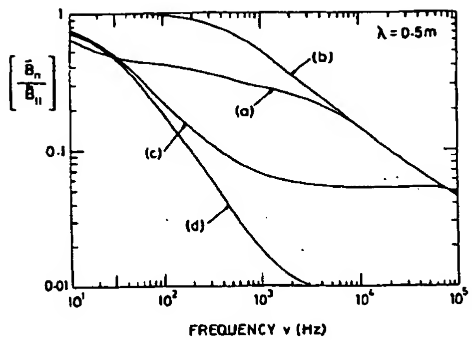

FIG. 5. Ratio of perpendicular to parallel fluctuating edge magnetic fields versus frequency for various wall structures. (a) Bellows and thick shell (HBTX1B), (b) Bellows and thin shell (HBTX1C), (c) 2 mm copper shell, 2 mm gap, 3 mm smooth graphite, and (d) 2 mm copper shell only.

doing this, not only will flux penetration from equilibrium field errors and thin shell modes be suppressed but also from the higher frequency fluctuating radial fields generated by plasma activity. Figure 5 illustrates the dependence of the ratio of perpendicular to parallel fluctuating magnetic fields on frequency. The calculations are performed for various wall configurations taking a wavelength of 0.5 m (corresponding to $n \sim 10$ in HBTX). In the figure, (a) represents the thick shell configuration (HBTX1B), (b) represents the thin shell configuration (HBTX1C), (c) represents a smooth copper shell (2 mm thick) separated from the plasma by 2 mm vacuum and 3 mm of graphite, and (d) represents the smooth copper shell at the plasma surface. Although option (d) is obviously the best at suppressing the radial field fluctuations, (c) is the practical solution for reasons of gap protection and impurity control. Option (c) provides ~sixfold reduction in the fluctuating radial field over the frequencies dominant in HBTX (i.e., 1–20 kHz). It is estimated, that this will reduce the value of ΔV_φ by ~5 V, to be compared with the minimum value achieved on an HBTX1B of ~10 V.

V. SUMMARY

The experiments on HBTX have highlighted the importance of minimizing the flux that can penetrate the plasma wall boundary. The loop voltage is found to increase proportionally with this flux that can arise from equilibrium field errors, from limiters in the plasma and from plasma activity. Helicity balance models provide a framework to understand this phenomenon.

Operation with a resistive shell leads to the growth of magnetic modes that generate a time-dependent flux penetration of the wall. This leads to an increasing loop voltage required to sustain the discharge and to early termination. Feedback stabilization of plasma position and of the $(m,n) = (1,2)$ thin shell mode have been successfully demonstrated.

A new first wall design is being developed for HBTX that will reduce sixfold the flux that penetrates the first wall from fluctuating magnetic fields and consequently minimize the loop voltage needed to sustain the RFP discharges.

ACKNOWLEDGMENTS

This paper is based on experimental and theoretical results produced by members of the HBTX group, by graduate students, and by visiting scientists who have been attached to the group. They are thanked for providing the data and for many useful discussions.

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Some Criteria for a Power Producing Thermonuclear Reactor

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Communicated by D. W. Fry; MS. received 2nd November 1956

Abstract. Calculations of the power balance in thermonuclear reactors operating under various idealized conditions are given. Two classes of reactor are considered: first, self-sustaining systems in which the charged reaction products are trapped and, secondly, pulsed systems in which all the reaction products escape so that energy must be supplied continuously during the pulse. It is found that not only must the temperature be sufficiently high, but also the reaction must be sustained long enough for a definite fraction of the fuel to be burnt.

§ 1. Introduction

It has been widely conjectured that some form of controlled thermonuclear reactor, capable of producing a useful amount of power, will some day be constructed. In this paper the power balance in such a reactor is considered, and some criteria which have to be satisfied in a power producing system are derived.

Some of the difficulties of realizing a controlled fusion reaction have been discussed by Thirring (1955) and Thonemann (1956), and a broad survey of fundamentals has been given by Post (1956). The present treatment differs from that of Thirring in the assumptions about the radiation from a hot gas, and it covers in rather more detail some of the points discussed by Thonemann and Post. The analysis is based on simple assumptions; it is designed to illustrate the essential features of the problem, and is neither rigorous nor complete. The assumptions made are in all cases optimistic, so that the criteria established are certainly necessary, though by no means sufficient, for the successful operation of a thermonuclear reactor.

§ 2. Basic Principles

Of the exoergic reactions involving light nuclei those between the hydrogen isotopes (the so-called D–D and T–D reactions) are by far the most probable at low energies. Of these the T–D reaction has the higher cross section, but since tritium does not occur naturally it is necessary to use a system in which it can be bred. This may be done by capturing the neutrons emitted in the T–D reaction in ^{6}Li, which then decays into T and ^{4}He.

The reactions of interest are shown in table 1.

Table 1

Reaction	Q (Mev)	σ_{max} (barns)	σ_{max} energy
^{2}H(d, n)^{3}He	3·3	0·09	2 Mev
^{2}H(d, p)^{3}H	4·0	0·16	2 Mev
^{3}H(t, n)^{4}He	17·6	5·0	150 kev
^{6}Li(n, α)^{3}H	4·8	$1/v$ law	

The energy released per unit time and volume by thermonuclear reactions in a hot gas is given by

$$P_R = n_1 n_2 \overline{v\sigma}(T) E \qquad \ldots\ldots(1)$$

where n_1 and n_2 are the number densities of the nuclei of the first and second kinds, and $\overline{v\sigma}(T)$ is the product of the relative velocities of the nuclei and the reaction cross section averaged over the Maxwellian velocity distribution corresponding to a temperature T, and E is the energy released by one reaction. If the ions are of the same kind (as in the D–D reaction) $n_1 n_2$ is replaced by $2(n/2)^2 = \frac{1}{2}n^2$. Values of $\overline{v\sigma}(T)$ calculated from published values of the cross sections for the D–D and T–D reactions are given in the companion paper by Thompson (1957).

Energy can be lost from the hot gas in two ways, by radiation and by conduction. At temperatures above about 10^6 degrees hydrogen is completely ionized and radiation occurs principally as bremsstrahlung (free–free transitions). The mean free path of such radiation is large (several g cm^{-2}) and consequently in a reactor of controllable size virtually all of it would escape. The Stefan–Boltzmann T^4 law does not hold under these circumstances; the variation of intensity with temperature can only be found by a detailed study of the radiation process. The power radiated per unit volume in hydrogen is given by (Spitzer 1956)

$$P_B = 1{\cdot}4 \times 10^{-34} n^2 T^{1/2} \text{ watts cm}^{-3}. \qquad \ldots\ldots(2)$$

If the hot gas is in a magnetic field the electrons will move in spiral orbits, and additional radiation due to the acceleration towards the axis of the spiral will occur. This radiation is similar to that obtained from electrons in a betatron, and it may be important in very intense fields. It will, however, be neglected in this paper.

Conduction loss is difficult to treat in a general way, since it depends on the geometry of the system, its density and temperature distribution, and also the wall material. In the analysis which follows it is optimistically assumed that the conduction loss is zero.

It is of interest to see at what temperature the nuclear power release is equal to the radiated power. This may be called the 'critical temperature' and is the hypothetical temperature which would be needed for a self-sustaining system if all the radiation escaped but the reaction products were retained. The critical temperature is about 150 million degrees for the D–D reaction (assuming that the tritium is burnt as soon as it is formed, but that the ^{3}He is not burnt), and 30 million degrees for the T–D reaction.

The critical temperature is a somewhat artificial concept; it does not mean that if a thermonuclear fuel is heated to this temperature a reaction will be set off in the way that a chemical explosion is set off, or that the fuel can be ignited as in a gas jet. This would only be true if the energy of the reaction were deposited close to where it was released, i.e. if the range of the reaction products were short compared with the dimensions of the apparatus. In fact, the range of the particles will almost certainly be large compared with the dimensions of the apparatus if the system is to be of controllable size, so that unless the tracks are somehow coiled up it will be the walls of the apparatus which are heated rather than the gas, and energy must be fed in continuously to sustain the reaction.

Various types of system will now be considered in a general way. No suggestions of how to realize them will be given.

§ 3. Systems in which the Reaction Products are Retained

It is not inconceivable that the charged reaction products could be contained in the hot gas by a suitable combination of electric and magnetic fields, though it seems unlikely that the escape of neutrons can be prevented. The temperature at which such a system would be self-sustaining in the absence of conduction loss can be calculated by equating the radiation loss to the energy carried by the charged disintegration products. This temperature is about 3×10^8 degrees for the D–D reaction, and 5×10^7 degrees for the T–D reaction. In the D–D system it is only just possible in principle to sustain the reaction, since above about 10^8 degrees the reaction rate increases with temperature only slightly faster than the radiation loss. At 10^9 degrees for example a conduction loss equal to the radiation loss is sufficient to quench the reaction.

As an example of the orders of magnitude involved, the slowing down range of the charged reaction products in a gas at 10^8 degrees and 10^4 atmospheres pressure ($n = 3 \times 10^{17}$ nuclei/cm^3) is of the order of a kilometre. The range of the neutrons is hundreds of kilometres.

§ 4. Systems in which the Reaction Products Escape

An alternative type of system in which the reaction products are not retained in the gas will now be considered. Since some specific proposals are for pulsed systems we shall consider the following idealized cycle: the gas is heated instantaneously to a temperature T, this temperature is maintained for a time t, after which the gas is allowed to cool. Conduction loss is neglected entirely, and it is assumed that the energy used to heat the gas and supply the radiation loss is regained as useful heat.

An important parameter R will now be introduced; this is the ratio of the energy released in the hot gas to the energy supplied. Now the energy released by the reaction appears as heat generated in the walls of the apparatus, and this has to be converted to electrical, mechanical or chemical energy before it can be fed back into the gas. If η is the efficiency with which this can be done, then the condition for a system with a net power gain is

$$\eta(R+1) > 1. \qquad \ldots\ldots(3)$$

The maximum value of η is about $\frac{1}{3}$, so that R must be greater than 2.

For the pulsed cycle described above we have

$$R = \frac{tP_R}{tP_B + 3n\boldsymbol{k}T} = \frac{P_R/3n^2\boldsymbol{k}T}{P_B/3n^2\boldsymbol{k}T + 1/nt} \qquad \ldots\ldots(4)$$

where P_R and P_B are respectively the reaction power and radiated power per unit volume. The $3n\boldsymbol{k}T$ term represents the energy required to heat the gas to a temperature T. Electron binding energies are neglected, but the contribution from electrons is included (this accounts for the factor 3 rather than $\frac{3}{2}$).

Since P_R and P_B are both proportional to n^2, R is a function of T and nt. In figure 1 curves of R against T for various values of nt are shown for the D–D reaction assuming that the tritium formed is also burnt. (In practice the tritium would have to be collected and fed back into the system with the deuterium.) The line $R = 2$ is shown dotted in the figure, and it is seen that for a useful reactor T must exceed 2×10^8 degrees and nt must exceed about 10^{16}. Thus, for a pulse of 1 microsecond duration, n must be greater than 10^{22}; this corresponds to

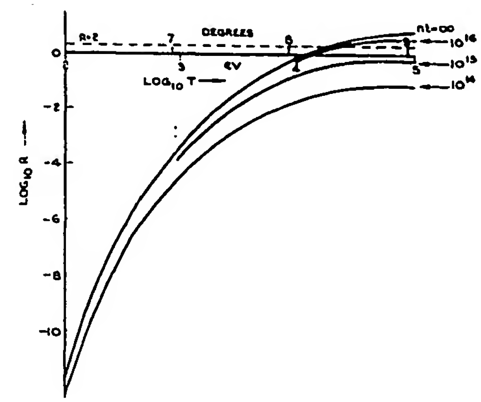

Figure 1. Variation of R with T for various values of nt for D-D reaction.

a pressure of 6×10^8 atmospheres at a temperature of 2×10^8 degrees. Particles move several metres during this time, and the mean free path for momentum transfer is several centimetres even at this high density. These distances are, of course, measured along the track, which may be spiralled or oscillatory.

Figure 2 shows similar curves for the T–D reaction. Conditions are easier, but still severe; nt must exceed 10^{14}, and the minimum temperature is 3×10^7 degrees.

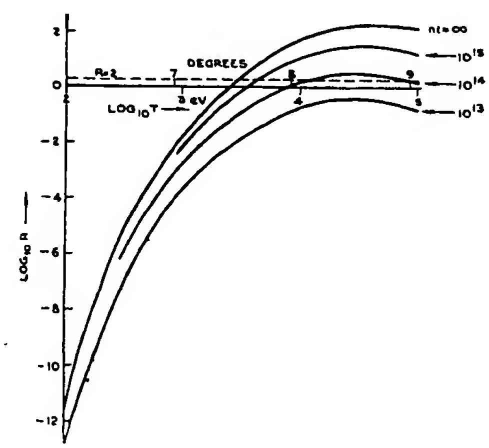

Figure 2. Variation of R with T for various values of nt for T-D reaction.

The curve marked $nt = \infty$ merely shows the ratio of the thermonuclear power release to the radiation loss, and crosses the $\log R = 0$ axis at the critical temperature. The curves are only accurate so long as t is sufficiently short that only a small fraction of the fuel is burnt. The values $nt = 10^{16}$ for a D–D system and 10^{14} for a T–D system both correspond to a burning of about 1% of the fuel.

Although these calculations refer specifically to a system in which the reaction products escape, it may easily be verified that the '1% burn-up' criterion is

almost unaltered in a system in which the reaction products are retained. In any practical system, where conduction loss is present, and where a large circulating power in the system is undesirable, the fraction of fuel burnt would need to be much greater.

§ 5. Conclusion

For a successful thermonuclear reactor not only has the temperature to be sufficiently high, but also the reaction has to be sustained for a sufficient time. The reason for this is that the organized energy used to heat the gas is ultimately degraded to the temperature of the walls of the apparatus and, consequently, sufficient thermonuclear energy must be released during each heating cycle to compensate for this degradation.

No claim that the above treatment is complete or applies to all possible types of system is made, but it does give some idea of the order of magnitude of the problems involved.

Systems which depart substantially from the electrically neutral Maxwellian gas assumed here have been carefully considered, but none looks promising. Some reasons for this are discussed by Thonemann (1956).

Acknowledgments

This paper is an amplified version of the more important topics in A.E.R.E. report GP/R 1807. It owes much to discussions with several colleagues, in particular Mr. R. S. Pease, Dr. W. B. Thompson and Dr. P. C. Thonemann.

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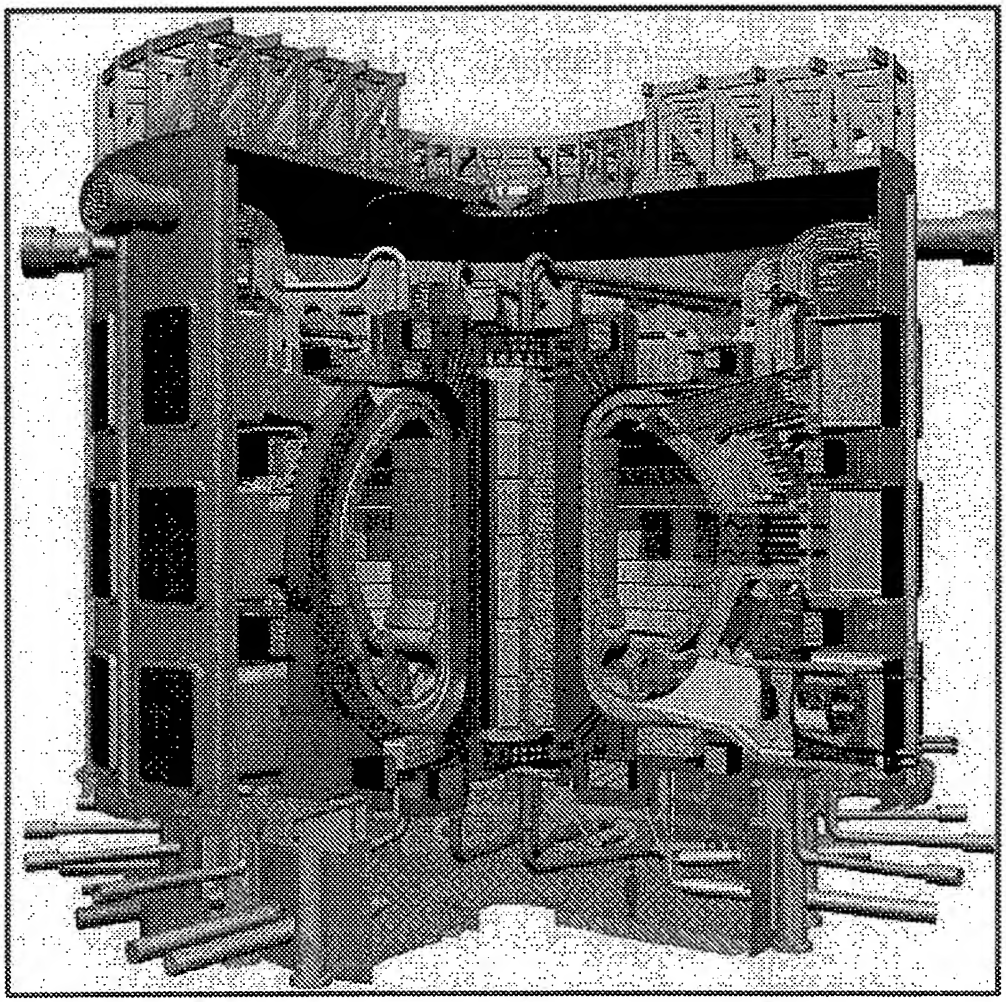
International Research Co-operation in the Field of

CONTROLLED THERMONUCLEAR FUSION

25TH REPORT COVERING 2002

(FEBRUARY 2003)



ITER: International Experimental Thermonuclear Reactor

FEDERAL OFFICE FOR EDUCATION AND SCIENCE

CONTENT

EN BREF

- Les ITER CTA (*Coordinated Technical Activities*) se sont achevées avec succès et les partenaires internationaux (Canada, Fédération de Russie, Japon et Union européenne) se sont mis d'accord sur les ITA (*ITER Transitional Arrangements*) qui constituent, dès le 1er janvier 2003 et avant que ne soit créée l'ILE (*ITER Legal Entity*), la base légale pour la poursuite de la collaboration internationale préparant la prochaine grande installation de recherche.

- Le Japon a proposé officiellement de construire ITER à Rokkasho-mura, dans la partie nord de son île principale, ce qui porte maintenant à quatre le nombre (probablement définitif) des sites candidats; à part le site japonais, il s'agit de Cadarache (France), Clarington (Canada) et Vandellòs (Espagne).

- Tout au long de l'année, la Chine et les U.S.A. ont exprimé une volonté croissante de s'associer au projet ITER et des déclarations officielles à cet effet sont attendues pour le début de l'année 2003[1]; il est intéressant de noter que le scénario "fast track", qui prévoit une commercialisation de l'énergie de fusion 20 ou 25 ans plus tôt que le calendrier actuel (50 ans), suscite un intérêt considérable aux U.S.A.

- Le 3 juin 2002, le Conseil de l'Union européenne a adopté le 6ème programme cadre de recherche et de formation de la *Communauté européenne de l'énergie atomique* (Euratom) dans le domaine de l'énergie nucléaire et confirmé un budget de 750 millions d'€ pour la fusion; sur cette base, la Commission européenne a fixé à 20 % (40 % pour les activités prioritaires) le niveau du soutien communautaire aux activités de recherche effectuées dans les laboratoires nationaux associés au programme; c'est là une diminution sensible par rapport aux niveaux du 5ème programme cadre (25 et 45 %).

- Le 9 décembre 2002, le Conseil fédéral suisse a adopté la prolongation de quatre accords avec Euratom en matière de fusion: le *European Fusion Development Agreement* (EFDA), le *JET Implementing Agreement* (JIA), le *Contrat de mobilité* et le *Contrat d'association*, assurant ainsi la poursuite d'une collaboration de longue durée.

- Le *Centre de recherche en physique des plasmas* (CRPP) de l'*Ecole polytechnique fédérale de Lausanne* (EPFL) a été choisi comme chef de file responsable par les différents laboratoires nationaux auxquels seront confiés le développement et la construction du système de chauffage du plasma d'ITER par onde cyclotron électronique.

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[1] Pour les U.S.A., c'est chose faite depuis le 30 janvier 2003.

KURZER ÜBERBLICK

- Die ITER CTA (*Coordinated Technical Activities*) wurden erfolgreich abgeschlossen, und die internationalen Partner (Japan, Kanada, Russische Föderation and Europäische Union) haben sich auf die ITA (*ITER Transitional Arrangements*) geeinigt. Seit dem 1. Januar 2003 bilden letztere die juristische Grundlage für die Fortsetzung der internationalen Zusammenarbeit, die den Bau und den Betrieb der nächsten grossen Forschungsanlage vorbereitet, bevor die ILE (*ITER Legal Entity*) in Kraft tritt.

- Japan hat offiziell Rokkasho-mura im nördlichen Teil der Hauptinsel als Standort für ITER vorgeschlagen; dadurch erhöht sich die (sehr wahrscheinlich definitive) Zahl der kandidierenden Standorte auf vier; neben dem japanischen Ort handelt es sich um Cadarache (Frankreich), Clarington (Kanada) und Vandellòs (Spanien).

- Während des ganzen Jahres haben China und die U.S.A. ein wachsendes Interesse an einer Beteiligung am Projekt ITER signalisiert; entsprechende offizielle Deklarationen werden für Anfang 2003 erwartet[2]; bemerkenswert ist die Tatsache, dass der sogenannte "fast track"-Zeitplan, der 20 bis 25 Jahre früher als der herkömmliche Zeitplan (50 Jahre) eine Vermarktung der Kernfusionsenergie vorsieht, in den U.S.A. auf sehr grosses Interesse stösst.

- Am 3. Juni 2002 genehmigte der Rat der Europäischen Union das 6. Forschungs- und Ausbildungsprogramm der *Europäischen Atomgemeinschaft* (Euratom) im Bereich Kernenergie und bestätigte ein Budget von 750 Millionen € für die Fusion; entsprechend setzte dann die Europäische Kommission die Höhe der finanziellen Unterstützung zu Gunsten von Projekten, die in den mit dem Programm assoziierten nationalen Institutionen durchgeführt werden, auf 20 % (40 % für Prioritätsaktivitäten) fest; dies entspricht einer markanten Abnahme im Vergleich zum 5. Rahmenprogramm (25 und 45 %).

- Am 9. Dezember 2002 genehmigte der Schweizerische Bundesrat die Verlängerung von vier Abkommen mit Euratom auf der Gebiet der Fusionsforschung: das *European Fusion Development Agreement* (EFDA), das *JET Implementing Agreement* (JIA), den *Mobilitätsvertrag* und den *Assoziationsvertrag*; dadurch wurde die Fortsetzung einer langjährigen Zusammenarbeit gesichert.

- Das *Forschungszentrum für Plasmaphysik* (CRPP) der *Eidgenössischen Technischen Hochschule* in Lausanne (EPFL) wurde von den verschiedenen nationalen Institutionen, die für die Entwicklung und den Bau einer Plasmaheizung für ITER auf der Basis von Zyklotronwellen verantwortlich sind, als führendes Laboratorium gewählt.

[2] Am 30. Januar 2003 haben es die U.S.A. getan.

IN SHORT

- The ITER CTA (*Coordinated Technical Activities*) have been successfully completed and the international partners (Canada, Japan, Russian Federation and European Union) have reached an agreement on the ITA (*ITER Transitional Arrangements*) which provide a legal basis as of 1 January 2003 for the continuation of the international co-operation on the next large research facility, until the ILE (*ITER Legal Entity*) comes into force.

- Japan has officially proposed a site for ITER: Rokkasho-mura in the northern part of the main island; thus, the (most likely) final number of candidate sites amounts now to four; besides the Japanese site, these are: Cadarache (France), Clarington (Canada) and Vandellòs (Spain).

- China and the U.S.A. have expressed throughout the year a growing interest in joining the ITER project and official announcements to that effect are expected for early 2003[3]; it is worth noting that the so-called "fast-track" scenario, which foresees a commercialisation of fusion power 20 to 25 years earlier than the current road map (50 years), is attracting a lot of interest in the U.S.A.

- On 3 June 2002, the Council of the European Union adopted the 6th framework programme of the *European Atomic Energy Community* (Euratom) for research and training on nuclear energy and confirmed that 750 million € will be attributed to fusion; on that basis, the European Commission set at 20 % (40 % for priority items) the level of support it will grant to research activities carried out in national laboratories associated with the programme; this is a significant decrease from the level of support granted during the 5th framework programme (25 and 45 %, respectively).

- On 9 December 2002, the Swiss Federal Council adopted the prolongation of four agreements with Euratom in fusion research: the *European Fusion Development Agreement* (EFDA), the *JET Implementing Agreement* (JIA), the *Mobility Agreement* and the *Contract of Association*, thus ensuring the continuation of a long-standing co-operation.

- The *Plasma Physics Research Centre* (CRPP) of the *Swiss Federal Institute of Technology* (EPFL) in Lausanne has been selected as the leading laboratory by the various national institutions in charge of developing plasma heating systems for ITER based on cyclotron waves.

[3] The U.S.A. have done so on 30 January 2003.

FOREWORD

In the field of controlled thermonuclear fusion research, the end of the 20th century was marked by a series of significant breakthroughs at a few large facilities, such as JET (*Joint European Torus*) in Europe, which demonstrated that fusion energy can be produced on Earth. The first half of the 21st century will see a new generation of devices which will definitely establish the technical feasibility and economic viability of harvesting fusion energy for commercial electricity production. So, in several respects, fusion research finds itself currently in a phase of transition characterised mainly by international negotiations and decision planning for the steps ahead rather than by scientific and technical highlights comparable to those of the preceding decade.

Thus, it seems a good opportunity to review past achievements and future challenges, to take stock of 40 years of fusion research and to assess the road map ahead. The occasion – and to a very large extent the material – for such an evaluation was given by recent developments within the *International Energy Agency* (IEA) of the *Organisation for Economic Co-operation and Development* (OECD). Two years ago, the *Committee on Energy Research and Technology* (CERT) of the Agency asked its *Fusion Power Co-ordinating Committee* (FPCC):

« When will fusion power be available?
– What are the steps needed to get there?
– Why does it take so long? ».

A drafting party of the FPCC then produced a two page summary, endorsed by the FPCC, which is meant to become the official position paper of the IEA on nuclear fusion. It also wrote a more detailed, ten page chapter which will be part of an IEA book devoted to the options available in this century for mitigating greenhouse gas emissions (*Energy Technology: Facing the Climate Challenge*). The short and the full reports together make up chapter 1 of the present report and give an overview of the current status of fusion research.

Against this background, the significant events of last year in the world of fusion research are reviewed in chapter 2 with an emphasis placed on the next large facility (ITER) and on the Euratom fusion programme. Chapter 3 then summarises the noteworthy events in Switzerland in 2002 and the report closes with the usual list of contacts for the interested readers who wish to have more information.

As it is sent to a large, multilingual readership, the report is published for the first time in English rather than in French or German, with only brief summaries in these two languages. Readers who have strong feelings about this, either for or against, are kindly asked to let us now. It will help us make a final decision on that issue in one or two years.

Like every year, the author is indebted to Prof. Minh Quang Tran, Director of the *Plasma Physics Research Centre, Swiss Federal Institute of Technology* in Lausanne, and to Prof. Peter Oelhafen, *Department of Physics* of the *University of Basle*, for most of the information of chapter 3 and for the figure on the cover.

Dr. Jean-François Conscience
Federal Office for Education and Science

CHAPTER 1

FUSION POWER: WHERE DO WE STAND ?

Prospects for Fusion Electricity

The **Short Report** was prepared by the *Fusion Power Co-ordinating Committee* of the *International Energy Agency* (IEA) for the *Governing Board* of the Agency.

The **Full Report** is adapted from a chapter on nuclear fusion which will be part of a report on energy supply for the 21st century prepared by the *Committee on Energy Research and Technology* of the IEA, to be published in late 2003 or early 2004 under the title *Energy Technology: Facing the Climate Challenge.* Authors of the original chapter are Ian Cook, *United Kingdom Atomic Energy Agency*, Gunnar Leman, *Swedish Research Council*, Masayuki Nagami, *Japan Atomic Energy Research Institute*, Serge Païdassi, *European Commission*, and Michael Roberts, *United States Department of Energy.*

Both texts have been revised to fit into the present report and full responsibility for the versions included here rests entirely with J.-F. Conscience

SHORT REPORT

When will fusion power be available? The question is today of particular interest as the international community will soon be asked to invest 4'500 million € in the *International Thermonuclear Experimental Reactor* (ITER). Under the auspices of the *International Atomic Energy Agency* (IAEA), the milestone project, now in negotiation, will be a joint venture of many countries with, as main partners, Canada, China, the European Union (EU) including Switzerland and several candidate countries, Japan, the Russian Federation and the U.S.A. The design of what will be the first fusion reactor producing significant amounts of energy was completed in June 2001, and sites for hosting the facility have been offered by Canada, the EU (in France and in Spain) and Japan.

The facts

Technical feasibility – Production of fusion energy has been demonstrated in experimental devices at levels of up to several megawatts for short time spans. Scientific and technological know-how, leading to an agreed design, is now available for the construction of the first experimental reactor, ITER, in order to demonstrate that harvesting power from thermonuclear fusion is indeed scientifically and technically feasible. Thus, fusion energy generation on a commercial scale is not dependent upon further scientific breakthroughs; it is a matter of research and development to optimise existing concepts and technologies, and it requires both large international facilities and strong domestic programs of supporting research. As materials with high irradiation resistance and low neutron-induced activation are of particular importance for highly performing, environmentally benign and economically attractive power plants, an *International Fusion Materials Irradiation Facility* (IFMIF) is being designed to test materials for fusion.

Safety – Extensive studies have shown that fusion is inherently safe and environmentally friendly. Initiating and maintaining fusion reactions require a number of such highly uncommon physical conditions that failure of components or uncontrolled operation immediately leads to reactor shut down. Although a fusion reactor contains significant amounts of tritium – a radioactive isotope of hydrogen, which, together with non-radioactive deuterium, makes up the fusion fuel – the worst in-plant generated accident would result in limited hazards to the public. Similarly, the consequences of accidents caused by external events, such as a very large earthquake, would be far less severe than those of the event itself. Finally, fusion fuels or materials are not subject to non-proliferation treaties because none of them poses a security threat with respect to nuclear weapon development.

Environment – The fusion reactions produce no greenhouse gas and no radioactive or toxic products, but neutron-induced radio-activation of the inner reactor walls does occur. Almost all of the activated materials, however, can be disposed of as inert waste, recycled, or given shallow-land disposal a few decades after the end of operation. Further, it is reasonable to expect that future research on materials will optimise this aspect.

Security of fuel supply – Tritium is produced in the fusion reactor from lithium, an element which, like deuterium, is plentiful, widespread and available at low cost. It is recalled in this context that fusion reactions release huge amounts of energy: 0.1 ton of deuterium and 4 tons of lithium would be enough to fuel for one year a 1000 megawatt electrical power plant requiring today 2.1 million tons of coal, or 10 million barrels of oil, or 100 tons of uranium.

Economics – The estimated costs of ITER have been validated by industry. The final costs of fusion electricity are estimated by extrapolating from the ITER costs and will depend upon the extent to which fusion physics, technologies, and materials are further optimised in the next few decades. Despite these uncertainties, current evaluations show that fusion electricity would be competitive in the future energy market. This is all the more so if emission mitigation costs such as carbon sequestration or external costs (e.g., environmental damage, adverse health impacts) are taken into account, and the significance of these costs is expected to grow in the future. Under these conditions, the projected cost of fusion electricity is comparable to that of other, environmentally friendly sources, thus ensuring it a significant share of the market by the end of the century.

Social acceptance – Ongoing social studies indicate that no specific public acceptance problems are expected for fusion if comprehensive information is available and if the public is actively involved in the decision process at an early stage.

The questions

« *When will fusion power be available?* » Despite significant progress, it is an acknowledged fact that the practicality and economical feasibility of harvesting fusion power remain to be demonstrated. ITER construction and operation are major steps toward that goal. The experimental reactor is designed to be a flexible test facility capable of producing a significant amount of thermal power (500 megawatts) under conditions mimicking those of a power plant. After about 10 years of construction, it will be exploited for 10 to 20 years, and, combined with the materials development programme, it will tell whether a demonstration power plant can be brought on line approximately 35 years from now. This would then lead to the first prototype commercial power plant toward the middle of the century. Stronger political will, leading to quicker decisions and heavier initial investments, could shorten markedly the development time ("fast track" scenario).

« *Why is it still so far away?* » Since the 1960's, fusion research has often been perceived as an expensive, moving target, because the fusion community regularly had to revise its estimate of the time needed to bring the technology to maturity. With the benefit of hindsight, it is easy to understand why. The most important factor was the initial lack of knowledge in the state of matter to be reached in order to allow a fusion power plant to work. The construction of a series of experimental devices has enabled the building up of the necessary experimental data and the testing of theoretical models which allow now to undertake with confidence the development of fusion as an energy source.

« *Why invest in fusion?* » The difficulties in solving the vital problem of providing energy for the future, with assurance of a secure supply while avoiding climate change, are universally recognised. No technological options can be ignored and, among these, fusion is a principal candidate for major contributions to the energy future, in particular for the centralised supply of base-load electricity. Indeed, socio-economic studies of long-term energy scenarios show that the cost, including externalities, of satisfying energy demand without fusion would be huge, dwarfing the cost of fusion development.

« *How is fusion research co-ordinated?* » Worldwide co-operation on fusion is established primarily within the framework of the IAEA and the IEA. The IEA *Fusion Power Co-ordinating Committee* co-ordinates the activities of eight *Implementing Agreements* fostering international co-operation on many fusion-relevant topics. One of these agreements, devoted to fusion materials, is the technology incubator for IFMIF. Several countries have national fusion research programmes which, in Europe, are largely integrated into the Euratom fusion programme of the European Union.

Introduction

Energy supply must be geared to ensuring the uninterrupted physical availability of energy products, at a price that is affordable for all consumers, while respecting environmental concerns and looking towards sustainable development. Such considerations have recently highlighted the weaknesses of many of the major current energy sources. Sustained economic growth and the development of electricity consumption are contributing to the increase in greenhouse gas emissions and it is much more arduous to reverse this trend than it might have seemed some years ago. Climate change and the security of fuel supply are major challenges and a long-term battle for the international community.

The need for new non-polluting and sustainable forms of energy to reduce the energy dependency of developed countries, to promote economic development and to contribute to climate change minimisation is therefore growing. Key elements of a responsible energy policy include the following: (1) optimising the use of present technologies to minimise environmental impact; (2) improving existing technologies, particularly in reducing pollutant emissions and increasing efficiency of energy production and use; and (3) developing a range of new technologies providing the options necessary to allow a gradual move to a radically different energy supply system and market.

Each potential technology for electricity production has pros and cons and all energy options have to be considered as potential contributors to an optimised future energy mix. Technologies for carbon sequestration are attractive options for possibly counterbalancing greenhouse gas emissions from fossil fuels, but their development is just starting. The harvest of renewable energy is already partly developed but there are issues associated with its availability, location and intermittence for a satisfactory integration into an electricity network. Nuclear fission is another available option although there are public concerns about its safety and the long-term issues of waste disposal.

Fusion, which would be particularly suited for the centralised supply of base-load electricity, appears as one of the most attractive long-term energy options because of the widespread distribution, abundance and low cost of its fuels and because of its significant favourable safety and environmental features. Thus, fusion energy would ideally complement renewable energy sources in the future energy mix. With the growth of the world population expected to occur in urban areas, concentrated energy sources that are not constrained with respect to where they can be located, such as fusion, may be particularly attractive.

As opposed to nuclear fission, fusion is a process that releases energy by joining together the nuclei of light elements, such as hydrogen and its isotopes, deuterium and tritium. It is the energy that powers the Sun and the stars, and the elucidation of the underlying scientific principles is one of the great achievements of 20th century physics. In so-called magnetic fusion[4], fusion reactions between deuterium and tritium nuclei take place in a

[4] This paper treats only magnetic fusion energy, reflecting the co-ordinated activities conducted by the IEA-FPCC. Inertial fusion energy represents a truly different scientific and technological approach. The direct funding for developing inertial fusion energy has been significantly less than for magnetic fusion, and much of the progress in this field has resulted from the investments made in some countries in inertial confinement studies for defence applications. Relative to magnetic fusion energy, only a small number of countries have formal inertial fusion energy programs. Additional information can be obtained from the book *Energy from Inertial Fusion*, International Atomic Energy Agency, Vienna, 1995 (see also page 22).

plasma[5] confined by a magnetic field and produce helium (an inert gas), neutrons and energy. The latter is used to heat the plasma and, thus, keep the fusion reactions going, and the excess is harvested to produce steam which can then be used to generate electricity according to well established technologies. In addition, neutrons react with lithium in the reactor wall to produce the tritium needed. Fusion reactions generate neither greenhouse gases nor radioactive or toxic products[6], and are inherently safe. Indeed, with enormous and widespread fuel resources, and the projection of viable economics, fusion represents a major and attractive option for future sustainable energy generation.

The long-term objective of fusion programmes in the international community is the creation of prototype plants for power stations to meet the needs of society: operational safety, environmental compatibility, economic viability. During the last decade or so, very important scientific and engineering developments have taken place, confirming that fusion is now a credible energy option having the potential for clean, large-scale power generation. This report summarizes the findings of an assessment made by the *Executive Committee* of the *IEA Implementing Agreement on a Co-operative Programme on the Environmental, Safety and Economic Aspects of Fusion Power* and endorsed by the *IEA Fusion Power Co-ordinating Committee* (FPCC). The assessment aimed at determining when fusion power would make an attractive contribution to the future energy mix, and the steps needed to bring this about effectively. Main results of studies on safety and environmental impact issues, recent progress in developing the technology of fusion power and assessments of economic viability and social acceptance of fusion, in comparison with other energy sources, are outlined to substantiate these prospects.

Status of Progress in the Technology of Fusion

There has been great scientific and technological progress in developing fusion over the last decade. Fusion power production has been achieved in existing devices such as JET (*Joint European Torus*) at levels up to sixteen megawatts, though only for short time pulses (seconds). Whilst reasonable advances in physics are anticipated, no further technical or scientific breakthroughs are needed to produce fusion energy at power station scale.

Past studies have established the scientific and technical basis for the construction of an international device of the next generation. The engineering design activities of such a next step, ITER (*International Thermonuclear Experimental Reactor*), have been completed. The facility will demonstrate the scientific and technological feasibility of fusion energy through the achievement of long pulses of burning plasmas and the integration of key fusion technologies. Its cost is estimated at 3'500 million € to which approximately 700 million € must be added for personnel, research and development expenditures during the construction phase. Yearly operation costs are currently estimated at 240 million € and will cover personnel (about 33 %), energy supply, tritium purchase, maintenance and waste disposal. Finally, after 10 or 20 years of operation, 430 million € will have to be spent on the dismantling of the facility.

Prototypes of most of the key components of a fusion power plant have been produced and successfully tested individually at close to the operating conditions. What is now needed are, firstly, the tests in ITER of tritium generation and energy extraction from blanket (plasma-facing inner wall of the reactor) modules prototyping the full size blanket of the

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[5] A plasma forms when a gas is heated to such high temperatures (above 100 million °C) that atoms are stripped of their electrons.

[6] Activation of the reactor walls does occur, though: see p. 13.

future demonstration power plant and, secondly, the development of low activation and radiation resistant materials and their testing in conditions as close as possible to those of a fusion power station.

A materials research programme is of particular importance to provide solutions for a sustainable, environmentally benign and economically attractive fusion energy technology. In addition to the essential information provided by ITER on plasma facing materials, it is necessary to develop high performance, low activation materials for machines after ITER. This programme should be run in parallel with ITER, to ensure that the materials are ready when required, and should include new materials concepts. Low activation structural steels and vanadium alloys with good physical properties have already been produced, and irradiation testing in fission reactors has started. However, irradiation testing using appropriate high energy, high intensity neutron sources (such as the *International Fusion Material Irradiation Facility*, IFMIF, currently being designed under IEA auspices) is required to test and verify material performance when subjected to extensive neutron irradiation of the type encountered in a fusion power station. Before that, useful studies can be done using neutron spallation sources, in combination with modelling of radiation damage studies. The cost of IFMIF should amount to less than a fifth of that of ITER or well below 1'000 million €.

The main research thrust centred around ITER and IFMIF needs to be complemented by a strong accompanying programme carried out in national laboratories and facilities around the world. Such a programme will address questions of basic, experimental as well as theoretical, plasma physics, design novel materials and study alternative concepts, such as stellerators or spherical tokamaks[7], which might turn out in the end to provide a better basis for future commercial reactors than the current tokamak design on which ITER is based. In addition, several national fusion research centres have developed expertise in key auxiliary technologies that will be as essential for future developments as they were in the past; the accompanying programme also has the aim of maintaining and improving such expertise.

Thus, fusion power generation on a commercial scale is not dependent upon further scientific breakthroughs but is a matter of reasonable research and development including system optimisation through technological engineering advances and scientific innovation. This, in turn, requires a well coordinated international approach combining the use of large facilities (ITER, IFMIF) and adequate support for strong domestic research programs.

Security of Fuel Supply, Safety and Environmental Issues

Fusion power would enhance energy security and diversification as its primary fuels, deuterium and lithium, are plentiful, widespread and available at low cost. One tenth of a ton of deuterium and ten tons of lithium would be enough to fuel for one year a thousand megawatt electrical power plant requiring today two million tons of coal, or ten million barrels of oil, or one hundred tons of uranium. For example, the amount of deuterium that could be extracted from Lake Geneva would be enough to satisfy Switzerland's electricity needs for several tens of thousands of years. Likewise, if the current total world electricity production was to be covered by fusion power stations, the amount of lithium needed

[7] The word "tokamak" is an abbreviation of the Russian phrase "toroidalnya kamera magnitnaya katuska" which means literally: toroïdal chamber magnetic coils. It is the most extensively studied concept for a magnetic fusion device, in which the plasma is heated in a doughnut-shaped chamber, and the most advanced facilities (JET, ITER, TCV, etc.) are based on that design; it is also a testimony to the important role played by Russian physicists, under the former Soviet Union, in the early stages of fusion energy research.

(approximately 3.8 tons per GW-year) would only be 25 % higher than the current pure lithium world production (6'000 tons per year), which represents a tiny fraction of world resources. Indeed, for all practical purposes, deuterium and lithium resources can be considered as quasi-unlimited.

There have been, during the last decade, many and extensive studies of the safety and environmental impact of possible future fusion power plants. These have convincingly shown that fusion has well-attested and attractive inherent safety and environmental features, as illustrated by the following points.

Fusion power stations will have only limited amounts of stored energy capable of driving accidents, as only a few minutes worth of fuel is present in the reaction chamber at any one time. It has been shown that the worst possible accident driven by in-plant energies would result in only very limited hazards to the public: maximal radiation doses would be comparable to those to which each individual is exposed every year from natural sources. Furthermore, the initiation and maintenance of fusion reactions requires such highly uncommon physical conditions that catastrophic spontaneous reactions are impossible and immediate shut down would follow a reactor failure. Finally, the consequences of a fusion plant accident caused by an external event such as a very large earthquake would be much smaller than the damages directly caused by the external event itself.

The operation of fusion power stations will make no adverse contribution to global climate change as no greenhouse gases are produced. The fusion process itself produces no radioactive or toxic reaction products. Although there is neutron-induced radio-activation of the machine structure during the plant operations, this would be sufficiently short lived that almost all, if not all, the materials in a fusion power station could be disposed of as non-radioactive waste, or recycled, or given shallow-land disposal a few decades already after the end of the plant life. There will not be a large waste burden for future generations.

Fusion power plants will make no use of uranium, plutonium or other fissile materials. None of the materials required are subject to the non-proliferation treaties, because none of them poses a security threat with respect to nuclear weapon development, a fact which also minimises the likelihood of a terrorist attack. Even small quantities of fertile or fissile materials illegally introduced into the plant could be readily detected since, as opposed to fission power station, these are not normal components of a fusion reactor.

One of the fusion fuels, tritium, an isotope of hydrogen which is produced in the fusion chamber by neutron-induced transmutation of lithium, is indeed a hazardous gas because of its radioactive nature. However, it has been the object of decades of study and, as a result, safe handling procedures are now well established. Furthermore, tritium is a short-lived radioisotope and, because of its continuous generation and consumption in the fusion reactor, it never accumulates to high levels and must not be stored and supplied from external sources.

The above safety and environmental advantages are already today a reality when power stations are designed using materials such as the reduced activation ferritic-martensitic steels that have been produced by industry for further qualification and which have been developed from experience accumulated with similar materials in nuclear fission technology. It is reasonable to expect that further safety and environmental advantages will be secured through the continuing development of these steels (e.g., micro-structural engineering) and through the development of advanced materials, such as vanadium alloys or silicon carbide composites.

Economics of Fusion Electricity

In the last few years, the economics of fusion electricity have been intensively studied and the main conclusions are summarised below. These investigations were performed in a way that was as independent of fusion programmes as was technically possible. The economic methodology, codes and calculations were standard, as recommended by several international agencies, including the IEA, and were verified by non-fusion experts. The components of economic performance fall into three areas: the internal costs of electricity generation; the associated external costs and the role of fusion power in total-cost-minimising future energy scenarios.

The term "internal costs" refers to the contributions to the cost of electricity from constructing, fuelling, operating, and disposing of, power stations. These direct costs of electricity generation by fusion, estimated currently by extrapolation from ITER costs, will eventually depend upon the extent to which fusion physics and materials are further optimised in the next few decades and this introduces inevitable uncertainties in making projections. However, the best available calculations show that, given only modest optimisation of fusion physics (which can be anticipated from current trends and would allow to achieve sufficient power plant availability) and use of materials currently in development, the direct costs of fusion electricity would be competitive in a future energy market. Comparing the projected costs of electricity from energy sources producing base load power, the fusion costs are roughly comparable to those from clean (pollution abated) coal plants and about fifty percent larger than those from fission. They are also comparable to the published costs of electricity produced from typical renewable energy sources, even when a projected future decrease in the costs of renewable energy is introduced into the calculations. Furthermore, the same calculations show that the use of advanced materials, technology and physics would further decrease the direct costs of fusion electricity, approaching the costs from fission or unabated fossil fuels.

The internal costs of electricity generation do not include costs such as those associated with environmental damage or adverse impacts upon health. In the case of some of the present sources of electricity, these "external costs" are substantial and appreciation of their importance has become widespread in recent years. The external costs of fusion electricity – and the role of fusion in cost-minimising future energy scenarios – depend strongly upon fusion's safety and environmental characteristics. These issues can be assessed essentially without reference to any further developments in fusion physics or materials, since the full expression of the safety and environmental advantages of fusion can be gained with existing physics and only very modest and confirmatory materials development.

Fusion external cost calculations have been performed only for Western Europe and may yield significantly different results elsewhere. Nevertheless, they show that fusion, along with wind, belongs to the class of low external cost sources. By comparison, the external costs of electricity from present European coal-fired plants are twenty times greater, and about half of them is attributed to climate change. Since external costs of a given technology increase broadly in proportion with levels of gross domestic product per capita, but internal costs are only weakly so dependent, the relative importance of external costs is expected to grow in the future.

Public Acceptance and Potential Share of Fusion in the Future Energy Mix

External costs associated with climate change are particularly uncertain. An alternative way of taking such issues into account is to investigate the consequences of imposing constraints on the amount of electricity production that is allowed to take place from specific sources, and this method can also be used to introduce constraints arising from social acceptance problems.

Exploratory studies on social acceptance of fusion technology were initiated a few years ago in some countries. Social science investigations and experiments were performed at local level including involvement of the public in the decision process on the installation of large energy facilities. Past experience with (fission) nuclear energy as well as with large fusion experimental plants were taken into account. According to preliminary results, no specific public acceptance problems are expected for fusion if (and this is a significant "if") comprehensive information is made available and the public is actually and meaningfully involved in the decision process at an early stage. Of course, fusion energy decisions could also become caught up in broader political issues over energy.

To assess its market potential, fusion power was incorporated into existing self-consistent economic models that determine the optimal energy and technology mix to minimise costs and emissions in a competitive market. In such models, constraints may be imposed on energy production from specific sources to take into account technology limits, investment capability, environmental policies and social acceptance problems.

In studies using this approach, fusion power was introduced into modelling of energy scenarios, up to the end of this century, for Europe, North America, the Asia-Pacific region, India and world-wide. The most important constraints applied in these studies were on greenhouse gas production. As the operation of fusion power stations does not produces such gases, it is not affected by this constraint. A range of constraints was applied to nuclear fission, to reflect possible social acceptance difficulties. Because of fusion's favourable safety and environmental features, it was assumed not to be subjected to these constraints. On the other hand, an important constraint was applied to fusion relating to limits to the speed with which it could be deployed.

These studies show, broadly, that fusion could bring a contribution of about twenty percent of the electricity supply by the end of this century, mainly constrained by the assumed rate at which it could be deployed (essentially, whether it develops along a "fast track" or along the reference roadmap: see below). This result holds even when a major role is allocated to nuclear fission. However, fusion would capture little or none of the market if there were neither environmental constraints nor economic development. Since the environmentally-constrained scenarios were constructed to be economically optimal, satisfying the demand without fusion would be much more expensive: the sums involved are huge, dwarfing the costs of fusion development.

The results coming from all the economic studies indicate that completing the development of fusion would bring substantial economic benefits. The amount of further optimisation in fusion physics and materials needed to secure these benefits depends upon the expected external costs of other power sources and upon the constraints placed on their deployment arising from social acceptance factors and the need to control environmental degradations. In regions with high externalities, such as Japan or Europe, or if environmental impact and/or social acceptance become predominant constraints, the economics of fusion power would be attractive given only modest and readily anticipated further optimisation of the

technology. Additional developments in fusion physics concepts and advanced fusion materials would then bring further economic benefits.

Road Map for a Practical Development towards Fusion Electricity

Although the achievement of commercial fusion energy has often been criticised in the past as being an unreachable moving target, it is fair and accurate to state clearly that the scientific basis for fusion is much more firm now than it was a decade or so ago. Today, there is a credible predictive capability based on key results, simulation models, diagnostic measurements and detailed comparisons between theory and experiment.

The current reference roadmap towards commercial fusion electricity production foresees three successive generations of devices: first ITER, then DEMO, a power plant to demonstrate the operational feasibility, reliability and economic attractiveness of harvesting fusion energy, and finally PROTO, a commercial prototype power station. According to the baseline timetable, DEMO could achieve net electricity production about 35 years after the decision to construct ITER, and large scale electricity production could begin in the second half of the century. This reference roadmap also assumes that the parallel development of fusion materials and the demonstration of environmental and safety cases supporting wide use of fusion power are completed in time for DEMO. A few key figures illustrate the progress to be made. Whereas JET produced 16 MW of fusion power for 2 seconds in 1997 (Q[8] = 0.65), it is expected that ITER will produce 500 MW for 400 seconds ($Q > 10$) and DEMO, 2 GW in continuous operation ($Q = 20\text{-}50$).

The major technical progress, in both the physics and technology of fusion, made during the last decade and summarised above, has brought about a realisation that a "fast-track" development of fusion is now possible, if this is desired, if the necessary political decisions are swiftly taken, and if the corresponding investments are made in a timely fashion. Eventually, the total amount of funding to reach the long-term objectives could be reduced substantially, but at the cost of increased short-term funding.

When looking towards energy production on such a faster road map, the ITER project remains the essential next step, and construction of the facility should start as soon as reasonably achievable. It is designed to be a flexible test facility to demonstrate fusion physics at power-plant relevant scale, to produce a large amount of thermal power (500 MW) and to test key technologies and components of fusion power plants. The engineering design has been finalised, and a modest upgrading could be readily achieved over the life of ITER, by fully exploiting the inherent flexibility of its present design. Technical feasibility of fusion power would then be demonstrated on a 20 to 25 year timescale. With ITER, the emphasis will be placed on demonstrating sustained fusion power production and extraction, and the facility will serve as an enabling research machine regardless of the design of later commercial power plants possibly derived then from alternative concepts, such as stellarators and spherical tokamaks.

Furthermore, earlier commercialisation of fusion electricity is regarded as possible if key steps are combined or taken in parallel. In particular, an attractive option would be to combine DEMO and PROTO into a single step that should be designed as a credible prototype for a power producing fusion plant, albeit in itself not yet fully technically and economically optimised. The feasibility of such an option depends strongly on the development of adequate materials. Thus, it is imperative, in a fast track scenario, to

[8] Q is the ratio of the fusion power produced over the external heating power provided to the plasma; this ratio shows that ITER will be the first machine producing an excess of power; for a fusion reactor, Q should be in the range of 40.

initiate the detailed engineering design activities of IFMIF in parallel with ITER construction and, once done, to build the facility without delay.

Conclusion

Until roughly the past decade, the development of fusion was held back by several technical difficulties. The most important was the initial lack of knowledge of the state of matter to be reached in order to allow a fusion power plant to work. The construction and operation of a series of experimental devices, and the testing of theoretical models on these devices, has resulted in the building up of the necessary experimental data and a predictive capability that allow us now to undertake with confidence the development of fusion as an energy source.

Indeed, in the last ten years, the dominant factor delaying the development of fusion has not been scientific or technical obstacles but the lack of effective commitment and decision-making at all political levels. In addition, fusion budgets, which account for about 11 % of the total spending on energy technology R&D in OECD countries, have been decreasing from 1'000 million US$ to less than 700 US$ between 1990 and 1999. Without these serious obstacles, ITER would be a reality now.

Today, fusion development is an international effort attracting an increasing number of highly motivated actors. The core partners who have brought forward the current ITER design (Japan, Russia and the European Union, including Switzerland and most of the candidate countries) will soon be joined by Canada, the United States, China, Korea and possibly other countries as well (India, Brazil). Continued and expanding international collaboration is indeed needed to bring effectively fusion forward to the market. The time scale of the endeavour will be critically dependent upon the degree of synchrony achieved in the realisation of the two main next ventures: ITER and materials development, including IFMIF. This, in turn, is a matter of political will and financial means; the promises of fusion and the challenge of meeting future energy needs deserve that both be strong.

CHAPTER 2

FUSION RESEARCH IN THE WORLD

Introduction

Throughout 2002, the renewed interest in nuclear fusion as a credible energy option for the second half on the 21st century continued to grow, in spite of the fact that no major scientific or technical breakthroughs occurred. Attention was largely focused on ITER, and the ongoing negotiations for the realisation of the project made good progress.

Within Euratom, the major partner of Switzerland in fusion research, the year was mainly characterised by the final decisions about the 6th framework programme and the resulting renewal of the fusion research agreements.

ITER

Proposed almost 20 years ago by Ronald Reagan and Mikhaïl Gorbatchev at the 1985 Geneva Summit, the project led to a first concept finalised in 1998 which foresaw a 7'000 million € facility capable of achieving ignition, that is a burning plasma producing enough energy to sustain fusion reactions without external energy input. The United States, then, for a combination of scientific, political and financial reasons, decided to withdraw from the project, and the remaining partners (Japan, Russian Federation and European Union) launched a new EDA (*Engineering Design Activities*) phase which was concluded in 2001. The scaled down project now proposes to build ITER for roughly half the price of the initial concept. The revised machine will not reach ignition, but it will lead to the production of a ten fold excess of energy for up to several minutes. Furthermore, the facility will provide for ample testing of critical components for a future demonstration power plant.

The publication of the *Final Design Report* launched a phase of intensive negotiations between the partners, soon joined by Canada. Under discussion are the legal status and organisation of the future ITER management (the so-called *ITER Legal Entity* or ILE), the choice of the site and cost sharing issues. The negotiations have been ongoing throughout 2002 and significant progress has been achieved on a number of issues. The CTA (*Co-ordinated Technical Activities*) were completed at the end of 2002 and detailed planning of the facility will continue in 2003 under the ITA (*ITER Transitional Arrangements*) until the ILE enters into force.

As far as the site is concerned, assessments of the proposals made by Canada (Clarington near Toronto), France (Cadarache in Provence) and Spain (Vandellòs near Barcelona) were performed and extended to the Japanese site proposed in 2002: Rokkasho-mura in the northern part of Japan's main island. Not unexpectedly, all sites have been found to meet the technical specifications, and the decision will now move to a higher political level. The prospect for a European site, in particular Cadarache, appears quite good. The current planning still foresees that all critical decisions (ILE, cost sharing, site) will have been taken by the end of 2004, thus allowing ITER construction to start in 2005 or 2006.

It is a fact that the redesigned ITER project is attracting a lot of attention and is largely responsible for the mounting political interest in fusion in many countries. Indeed, even if official declarations to that effect were still pending at the end of 2002, it was clear that the U.S.A. would rejoin the project, that China and Korea would also start negotiating a participation, and that a number of other countries (India, Brazil) would express interest as well. Thus, ITER is likely to become a truly international project, of importance not only to highly industrialised economies but also for developing countries. Furthermore, it is noteworthy that the "fast track" road map to fusion commercialisation, outlined in the preceding chapter, is gathering even more support from the newcomers than from the core partners.

In December 2002, the ITER International Team Leader, Prof. Robert Aymar, was appointed Director General of CERN and will take office in January 2004. It is planned not to replace him but to appoint the Co-Leader, Dr. Y. Shimomura, Acting Leader, until the ILE enters into force and the ITER Director General is chosen.

Euratom fusion programme

Within the European Union, the *European Atomic Energy Community* (Euratom) has been responsible for almost 50 years for R&D activities in the field of controlled thermonuclear fusion. Although the corresponding programme is now part of the framework programmes, it is still a separate chapter subjected to the rules of the *Euratom Treaty* of 25 March 1957. This implies, for instance, that final decisions regarding programme content and funding are not taken by the European Parliament but by the Council of the European Union.

Accordingly, on 3 June 2002, the council gave final approval for the "*6th framework programme of the European Atomic Energy Community (Euratom) for nuclear research and training activities, also contributing to the creation of the European Research Area (2002-2006)*". The programme content includes the continuing exploitation of the large European tokamak, JET (*Joint European Torus*), in Culham (UK), the European participation in the design and planning of ITER, and a large fusion physics and technology section, including materials research and the investigation of magnetic confinement concepts other than tokamaks.

Two main instruments are used to execute the programme: (1) the *Contracts of Association* between the European Union and about twenty national fusion research institutions (the so-called "Associations"; for the situation in Switzerland, see next chapter) and (2) the *European Fusion Development Agreement* (EFDA), which deals mainly with the centralised activities around JET and ITER. These two instruments exemplify the peculiar situation of the Euratom fusion programme which includes both joint activities managed centrally by the European Commission and the EFDA leadership, and decentralised projects carried out in the Associations with the financial support of the programme.

With the June 3rd decision, a budget of 750 million € was definitely attributed to fusion in the 6th framework programme (FP6). Not only is this a significant decrease from the 5th framework programme (FP5; 788 million €), but the support to the national laboratories will have to weather a disproportionate share of the shortfall, since 200 million € of the total budget are set aside for ITER. In fact, compared to FP5, 40 % less funding is now available for the Associations. Consequently, soon after the decision, the European Commission decided to lower from 25 % to 20 % the level of its support to ordinary, approved national research activities, and from 45 to 40 % its support to priority items (defined as activities directly linked to ITER, or having been given priority status in the past, or carried out by more than Associations in co-operation). This evolution is placing practically all Associations in front of severe funding problems which will have to be solved nationally.

Because of the transition from FP5 to FP6, the implementing agreements covering the execution of the Euratom fusion programme all terminated at the end of 2002 and had to be renewed. Besides the *Contracts of Associations* and EFDA, three auxiliary agreements were also renegotiated: the *JET Implementing Agreement* (JIA), which covers the common use of JET by the Associations under EFDA, the *JET Operation Contract* (JOC) with UKAEA (*United Kingdom Atomic Energy Commission*), which pays for the operation of the facility by the British agency, and the *Mobility Agreement*, which, as in many other European programmes, encourages personnel mobility at all levels by granting travel and

secondment allowances. By the end of 2002, all agreements had been renewed, the *Contracts of Association* for one year and the others for two years.

In 2002, a new Director responsible for fusion within the Research Directorate General (DG XII) of the European Commission was appointed after a long vacancy. The Spaniard Pablo Fernandez Ruiz took office early in the year and has expressed since, on several occasions, a strong support for fusion. Finally, in 2002 Euratom negotiated successfully two co-operation agreements, one with Kazakhstan and one with Ukraine.

EFDA and JET

EFDA activities are very much focused on ITER and a whole range of supporting technologies (plasma heating systems, diagnostics, heat exchange, tritium generation, etc.). An important aspect of these activities is the exploitation of JET. Since the European tokamak is based on the same concept as the one which will be used for ITER, it has become an ideal test bed for ITER systems and components, and it has been widely used in 2002 for that purpose. The current arrangement, whereby UKAEA is operating the machine and the European Associations, under EFDA and JIA, are using it, has worked smoothly. Other activities under EFDA cover materials research, including the European participation in the design of IFMIF, and studies of alternative magnetic confinement concepts, such a stellerators.

In 2002, EFDA-JET has been an active member of EIROFORM (*European Intergovernmental Research Organisations Forum*: www.eiroforum.org), a loose association of the major European research facilities (CERN, ESO, ESA, EMBL, ESRF and ILL) which, among other activities, promotes public information. Thus, EFDA-JET participated in the initiative «Couldn't be without it ! »" which explains why many every day commodities would not be available without scientific and technological R&D.

Finally, at the end of 2002, the EFDA Leader, Prof. Karl Lackner, resigned to go back to his research activities, and the search for a successor is in full swing.

IEA and IAEA

IEA, an agency of OECD, plays an important role in coordinating worldwide various topics of fusion-related research via *Implementing Agreements* (IA's) between participating laboratories. Eight such agreements are currently in force and cover a broad range of fields including tokamak physics, materials for fusion (IFMIF), stellarators and other alternative concepts of magnetic confinement, plasma/wall interactions, socio-economic aspects, etc. (the site www.iea.org/impagr/imporg/impagpub/listof.htm#5 gives a list and a short description of current IA's in the field of fusion). Although the financial investment of IEA in those activities is modest, usually limited to administrative support, the importance of its co-ordinating role cannot be overemphasized. In 2002, the *Fusion Power Co-ordinating Committee* of IEA, which supervises the IA's, produced two interesting summaries of the current status of fusion research. This was in answer to a request by the *Committee on Energy Research and Technology* of the Agency and is the source of most of the information given in chapter 1 of the present report.

Besides providing administrative support to ITER, the **IAEA**, a specialised organisation of the United Nations, also has a number of activities related to nuclear fusion and steered by an advisory body, the *International Fusion Research Council* (IFRC). In 2002, the most visible event was the *Fusion Energy Conference* (FEC), which is organised every two years and which took place in October in Lyon, France.

Other international news

In the **U.S.A.**, as already mentioned, renewed interest for magnetic fusion made it practically certain, by the end of 2002, that it would rejoin ITER. The robustness of the current design did a lot to convince the Americans that the project is now scientifically, technically and financially sound, but the unwillingness of the Bush administration to impose significant penalties for energy wastage or to encourage seriously energy conservation measures was pulling at the same rope.

The U.S.A. is one of the few countries in the world which has a significant inertial fusion programme. In this totally different approach to generate fusion energy, small pellets of deuterium and tritium are compressed to enormous pressures, thus forcing atomic nuclei to fuse. The approach, which has mostly been investigated in the shade of military research (because the technology is also used to simulate thermonuclear explosions), is generally regarded as far less mature than tokamak-based magnetic fusion and still has to pass through a number of critical milestones to demonstrate its feasibility and practicability. Nevertheless, the U.S.A. is building (with huge delays and cost overruns) a *National Ignition Facility* (NIF) which will use intense laser beams to compress fuel pellets, whereas other US laboratories are investigating alternative approaches to compression, such as X-rays.

Finally, an article in *Science* magazine attracted some attention in the Summer of 2002. It was about an experiment at Oak Ridge National Laboratory in which fusion reactions reportedly occurred in solutions of deuterated acetone subjected to sound waves and neutron irradiation (so-called "table-top fusion"). To date, the results have not been reproduced though, neither by the original authors nor by any other laboratory, and it seems likely that table-top fusion will share the fate of "cold fusion" over a decade ago and fall into oblivion. Yet, the excitement it generated within a few days of publication is another sign of the very strong underlying eagerness to produce and harvest fusion energy.

In **Germany**, construction of the Wendelstein 7/X stellerator in Greifswald (Mecklemburg-Vorpommern) was considerably delayed by severe problems with the delivery of super conducting elements. As a consequence, the first operation of the facility is not expected before 2009-2010.

In **France**, the tokamak Tore Supra at Cadarache produced in June 2002 a 3.5 minute long plasma discharge: this is the world record of duration.

Finally, the *Symposium on Fusion Technology* (SOFT) gathered over 400 researchers in Helsinki in September 2002.

CHAPTER 3

FUSION RESEARCH IN SWITZERLAND

Introduction

Research in the field of controlled thermonuclear fusion is hardly possible today without broad international co-operation, especially for smaller countries like Switzerland. Accordingly, the Swiss activities in this field are practically entirely integrated into the EURATOM fusion programme of which Switzerland has been a full member since 1978. Furthermore, some research projects are carried out within the framework of *Implementing Agreements* of the IEA and, finally, there are also a number of activities done within bilateral or multilateral collaborations with other fusion research laboratories. All this is financed by the Swiss Federal Institutes of Technology (including Paul Scherrer Institute), by the Swiss National Science Foundation and by the EU.

Major player is the *Plasma Physics Research Centre* (CRPP) of the *Federal Institute of Technology* in Lausanne (EPFL) with its two sites at the EPFL and at the *Paul Scherrer Institute* (PSI) in Villigen, near Zurich. In Lausanne, besides a strong theory group, the CRPP relies on its large facility, TCV (*Tokamak with Variable Configuration*) to study basic fusion plasma physics. In fusion technology; the centre has acquired international recognition notably for its expertise in heating systems using cyclotron-electronic waves. At PSI, the interest of the CRPP group lies in materials research with the proton irradiation facility PIREX, and in superconductors with the worldwide unique test stand SULTAN.

With the financial support of the *Swiss Federal Office of Energy* (OFEN), a unit of the *Department of Physics* of the *University of Basle* has been co-operating for many years with the CRPP in studying surface changes resulting from exposure to hot plasmas. The group capitalises on the expertise it has acquired in photoelectron emission spectroscopy and related techniques to analyse graphite tiles coming from the inner wall of TCV.

Energy research in Switzerland is co-ordinated – and partly financed – by OFEN, but fusion research is under the supervision of the *Federal Office for Education and Science*, for this is the administrative unit which manages the participation of Swiss scientists to EU programmes. This is why the author of the present report acts as head of project for controlled thermonuclear fusion in the overall energy research organisation of OFEN.

Agreements between Switzerland and Euratom

The *Co-operation Agreement in the Field of Controlled Thermonuclear Fusion and Plasma Physics* between Switzerland and the European Atomic Energy Community (Euratom) of 14 September 1978 remains the legal basis for an ongoing co-operation which has led to an almost total integration of Swiss fusion research activities into the European programme. It is a broad agreement of unlimited duration unless denounced by one of the two parties. The work programmes and the financial boundaries of the research activities carried out under the agreement are defined in implementing agreements of limited duration concluded between the executive branches of both parties, namely, the Federal Council for Switzerland and the European Commission for Euratom. Currently, four such agreements are in force:

- The *European Fusion Development Agreement* (EFDA: see page 20);
- The *Jet Implementing Agreement* (JIA: see page 20);
- The *Agreement on the Promotion of Staff Mobility in the Field of Controlled Thermonuclear Fusion* (Mobility Agreement, see page 20);
- The *Contract of Association* which deals specifically with the bilateral co-operation between the CRPP and the Euratom fusion programme; formally, the work programme is carried out by the so-called *Association Euratom-Confédération Suisse*, which, *de facto*, means the CRPP.

All four implementing agreements terminated at the end of 2002 and had to be renewed for the start of FP6. The decrease in the community support to national activities (see page 20), resulting from the lower fusion budget in FP6 and the priority given to ITER, led to some tough negotiations to agree on the financial ceilings of the *Contract of Association*, but, eventually, the Swiss Federal Council could adopt the amendments to all four agreements on 9 December 2002. Whereas EFDA, JIA and *Mobility Agreement* have been renewed for two years until the end of 2004, the *Contract of Association*, as requested by the European Commission, is only in force for one more year and a further renewal will have to be negotiated in 2003.

Under these various implementing agreements, the yearly contribution of Switzerland to the Euratom fusion programme amounts to almost 10 million Swiss francs and is likely to remain at a similar level for the coming years. On 6 June 2002, the Swiss Parliament approved the budgets requested by the Federal Council to finance the participation of Swiss scientists in FP6 between 2003 and 2006, and these budgets also cover the Swiss contribution to Euratom. However, because of the decreased EU support for the research activities of the CRPP, an increase in domestic funding for the Lausanne centre is needed in order to ensure an unchanged level of activity. Ways and means to secure such an increase are currently being explored.

The Association EURATOM-Confédération suisse

Except for a small unit dealing with industrial applications of plasma physics (and whose activities are not reported here because they fall outside the scope of the Association), the CRPP is fully integrated within the Euratom fusion programme and its research plan is defined, in particular, in the *Contract of Association*. In Lausanne, the main emphasis is put on the experimental and theoretical study of hot plasmas but, as it is also essential to master technologies required to build a fusion reactor, two groups of CRPP at PSI are actively involved in superconductivity research and in the development and test of low activation materials. Besides its own research activities, the CRPP also participates, through EFDA and JIA, in the scientific exploitation of JET, in the ITER project and in other European and international co-operative projects.

The scientific output of CRPP has been widely publicised throughout the year in major international conferences and in numerous articles in specialised journals. The CRPP organised in June 2002 in Montreux the *29th EPS Conference on Plasma Physics and Controlled Fusion* of the *European Physical Society* with over 700 participants. A detailed report on the research activities briefly summarised below can be found in the Annual Report of the CRPP which can be accessed through its web site (crppwww.epfl.ch).

From an academic point of view, 2002 saw the integration of the CRPP in the newly created *Faculty of Basic Sciences* of EPFL. Finally, in September, CRPP was host to the *Swiss Federal Commission for Energy Research* (CORE), an advisory body to the government; through a visit of the facilities and through presentations given by the ITER International Team Leader, Prof. Robert Aymar, the Head of the fusion programme in the European Commission, Prof. Hardo Bruhns, and the Director of CRPP, Prof. Minh Quang Tran, the commission got a first hand and up to date report on the current status of fusion research.

Physics of Tokamak on TCV

Experimental tokamak physics research is performed using TCV, taking advantage of the unique capability of this state-of-the-art machine to produce hot plasmas with variable shapes. This is an attractive feature for the research programme which will accompany ITER construction and exploitation, and CRPP is thus well positioned to play an important role there.

In 2002, TCV was operated using its world most powerful cyclotron-electronic heating system at 3 MW (82.7 GHz) or 1.5 MW (118 GHz). Among the most salient results, mention is made here of:

- the extension of the operating range of TCV using cyclotron-electronic heating;
- further studies on the influence of plasma shape on its physical properties from edges to core;
- studies on the absorption of cyclotron-electronic waves at third harmonics;
- further important observations relating to density limits, ITER relevant H modes, divertor physics and internal transport barriers.

Theoretical Studies and Numerical Simulation

Investigations in these fields rely heavily on numerical simulation models using the most performing massively parallel computers available in Switzerland (at EPFL and at the *Swiss Centre for Scientific Computing* in Manno) and in Europe (*Max Planck Institute* in Germany).

Ongoing studies are aiming at:

- improving our understanding of transport phenomena in magnetically confined fusion plasmas: emphasis here is on abnormal transport caused by micro instabilities such as waves that have become unstable because of ionic temperature gradients;
- providing theoretical and interpretation support to experiments using TCV, JET or other tokamaks: here, plasma/cyclotron-electronic wave interactions, on the one hand, and neoclassical tearing modes, which can limit the performance of future fusion reactor, on the other hand, are main study topics;
- exploring new optimised tri-dimensional confinement structures: these studies concern not only the magnetic configurations themselves but also heating of the confined plasma by absorption of electromagnetic waves.

Plasma heating technology

Over many years, CRPP has acquired an internationally acknowledged expertise in the field of heating systems for magnetically confined plasmas using electromagnetic wave absorption at cyclotron-electronic frequencies. This has led to an active involvement of the Lausanne centre in the development of the corresponding wave sources, so-called gyrotrons, for TCV and other European facilities, such as *Tore Supra* in France or *Wendelstein 7/X* in Germany. For the latter, in co-operation with the *Forschungszentrum Karlsruhe* and the industrial firm *Thalès*, a gyrotron capable of delivering 0.85 MW during 180 seconds was tested at 140 GHz. This is a world record for this type of device.

Contributions to international projects

Through the Euratom fusion programme and, in particular, EFDA, CRPP is participating in most projects which are part of the programme, such as ITER, JET and other European facilities. Accordingly, and in spite of heavy commitments linked to the exploitation of TCV, CRPP was fully involved in the exploitation of JET.

As far as ITER is concerned, several members of CRPP participate as experts in scientific committees. Most importantly, CRPP was selected in 2002 by the European Associations to co-ordinate and integrate all European activities related to the development and procurement of cyclotron-electronic wave systems on ITERs. This will cover two aspects: (1) the development and test of gyrotrons and (2) the design of an appropriate antenna to target cyclotron-electronic waves into ITER plasma. To this aim, a test stand for gyrotrons and antenna components will be built in Lausanne.

Finally, CRPP, through its Materials Group at PSI, continued to be an active participant in the *IEA Implementing Agreement on Fusion Materials*, the Executive Committee of which is chaired by a CRPP-PSI staff member, Prof. M. Victoria. In this way, CRPP is actively involved in the design of IFMIF.

Development and test of superconductors

The SULTAN test stand of CRPP is also located at PSI and its operation is supported by PSI[9]. As the only facility in the world suitable for testing the super conducting cables of ITER, it will play a crucial role throughout ITER construction, and it is the intention of the European Commission to offer the quality assurance testing of all the cables at SULTAN as part of the European, in kind contribution to ITER construction.

In 2002, activities in the field of superconductivity have been focused around the development of niobium- and titan-based cables and cable junctions for ITER. Detailed studies using SULTAN of Nb_3Sn threads isolated from cables led to a better understanding of the problems which arise when one extrapolates from the properties of individual threads to those of the full cable.

CRPP expertise in this field also includes high temperature superconductivity. In 2002, 70'000 A current leads for ITER were designed using high temperature superconductors and will be tested in 2003 at the *Forschungszentrum Karlsruhe*.

Materials R&D for ITER and fusion reactors

A critical milestone of the road map leading to fusion reactors is the development of materials which, under heavy neutron irradiation, undergo only weak and short-lived radio-activation while keeping their thermo-mechanical properties unchanged. The Materials Group of CRPP located at PSI has a considerable interest in studying this problem. Again with the support of PSI, a proton irradiation facility, PIREX, has been exploited for many years. Obsolescence and the costly investments needed to refurbish it led in 2002 to a decision to phase it out at the end of 2003. A new agreement with PSI now allows irradiation studies to be done at the Swiss spallation source SINQ. Indeed, a recent study carried out in the framework of the *IEA Implementing Agreement on Fusion Materials* concluded that the use of such sources, combined with modelling studies, can yield useful results before IFMIF comes on line.

[9] A formal research agreement in the field of fusion between EPFL and PSI defines the level of support the latter institution grants to the activities of the CRPP Materials Group and Superconductivity Group.

A unique feature of PIREX and SINQ is the fact that, at both facilities, the formation of helium inclusions in metallic alloys and their influence on thermo-mechanical properties can be investigated. As this is viewed as a critical problem of future fusion reactors, CRPP is well positioned to play an major role in the corresponding studies. In this respect, priority is now placed on thermo-mechanical properties of ferritic-martensitic steels, such as Eurofer, which are the currently favoured materials for fusion reactors.

To interpret correctly the results of future neutron irradiation experiments using IFMIF, it is essential to compare the data of mechanical tests performed on small samples with those obtained with normalised probes, and this is another focus of the CRPP Materials Group at PSI. Finally, further research activities in this field include physical metallurgy, modelling of irradiation damages, the physics of fractures and electron microscopic studies of model metals or alloys.

Research done at the University of Basle

Within the *Physics Department*, the group of Prof. Peter Oelhafen has acquired considerable expertise in the use of photoelectron emission spectroscopy and related techniques, which are particularly suited to study surface phenomena. For many years, the group has been analysing graphite tiles coming from the inner wall of TCV in order to characterise the surface changes caused by exposure to hot plasmas, indeed a critical question for designing future fusion reactors. These studies were continued in 2002 with greater detection sensitivity and extended to a surface depth of 10 micrometers, thanks to the use of proton induced X-ray emission and Rutherford backscattering, in cooperation with a group at the University of Freiburg-in-Br. Whereas previous results regarding carbon, boron and oxygen were confirmed, the use of the new techniques revealed a very low and previously undetected level of surface contamination with iron, nickel, copper and chromium.

In addition, 2002 has seen the initiation of investigations with high Z-materials such as tungsten and, in later studies, vanadium: deposition techniques have been developed and tested. Finally, contacts have been re-established, after several years of interruption, with the *Forschungszentrum Jülich* in view of a renewed participation of the Basle group in studies carried out in the framework of the *IEA Implementing Agreement "Plasma/Wall Interactions in TEXTOR"*.

ADDITIONAL INFORMATION

The following web pages provide much additional information on all the topics discussed in this report:

Energy in general

International Atomic Energy Agency IAEA: www.iaea.org

International Energy Agency IEA: www.iea.org

Switzerland: www.suisse-energie.ch

ITER

www.iter.org

Euratom

European Fusion Development Agreement EFDA: www.efda.org

Joint European Torus JET: www.jet.efda.org

European Commission: europa.eu.int/comm/research/fusion1.html

Framework programmes of the European Union: www.cordis.lu

IEA Implementing Agreements

www.iea.org/impagr/imporg/impagpub/listof.htm#5

Switzerland

Plasma Physics Research Centre CRPP: crppwww.epfl.ch

University of Basle: monet.unibas.ch/oelhafen/

Interested readers can also contact:

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ABBREVIATIONS

CERN: European Laboratory for Particle Physics
CERT: Committee on Energy Research and Technology
CRPP: Plasma Physics Research Centre
CTA: Coordinated Technical Activities
DEMO: Demonstration fusion reactor
EDA: Engineering Design Activities
EFDA: European Fusion Development Agreement
EIROFORUM: European Intergovernmental Research Organisations Forum
EMBL: European Molecular Biology Laboratory
EPFL: Swiss Federal Institute of Technology in Lausanne
EPS: European Physical Society
ESA: European Space Agency
ESO: European Southern Observatory
ESRF: European Synchrotron Radiation Facility
EU: European Union
Euratom: European Atomic Energy Community
FEC: Fusion Energy Conference
FP5: 5th Framework Programme
FP6: 6th Framework Programme
FPCC: Fusion Power Co-ordinating Committee
GHz: gigaherz
GW: gigawatt
IA: Implementing Agreement
IAEA: International Atomic Energy Agency
IEA: International Energy Agency
IFMIF: International Fusion Materials Irradiation Facility
IFRC: International Fusion Research Council
ILE: ITER Legal Entity
ILL: Laue-Langevin Institute
ITA: ITER Transitional Arrangements
ITER: International Experimental Thermonuclear Reactor
JET: Joint European Torus
JIA: JET Implementing Agreement
JOC: JET Operation Contract
MW: megawatt
NIF: National Ignition Facility
OECD: Organisation for Economic Co-operation and Development
OFEN: Swiss Federal Office of Energy
PIREX: Proton irradiation facility
PROTO: Prototype fusion power plant
PSI: Paul Scherrer Institute
SINQ: Swiss spallation neutron source
SOFT: Symposium on Fusion Technology
SULTAN: Superconductor test stand
TCV: Tokamak with Variable Configuration
UKAEA: United Kingdom Atomic Energy Agency

CONTROLLED THERMONUCLEAR REACTIONS

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Gordon and Breach Science Publishers
New York

GORDON AND BREACH, SCIENCE PUBLISHERS, INC.
150 Fifth Avenue
New York, N.Y. 10011

Library of Congress Catalog Card No. 64–23922

This is a translation from L. A. Artsimovich: Управляемые Термоядерные Реакции published by Gosudarstvennoe Izdatel'stvo Fiziko-Matematicheskoi Literatury, Moscow 1961, second edition 1963

ENGLISH EDITION
First published 1964

Printed in Great Britain by
Hazell Watson & Viney Ltd, Aylesbury, Bucks

CHAPTER I

INTRODUCTION

§ **1.1** Thermonuclear reactions arise from collisions between the fast atomic nuclei in matter heated to a very high temperature. If the colliding nuclei have sufficiently large relative speed, they can overcome the potential barrier of mutual electrostatic repulsion, approach very closely to one another and react. When the temperature T is not too high, so that the quantity kT, representing the energy of the random thermal motion of the particles, has a value small compared to the barrier potential, only an insignificant proportion of the thermal collisions will result in nuclear reactions. As T is raised, the thermonuclear reaction rate increases rapidly.

Thermonuclear reactions are, apparently, the main source of stellar energy and must therefore play an important part in astrophysical processes. Inside stars, the temperature and the density are very high. Therefore in stellar matter an intensive process of nuclear synthesis must go on, during which the basic component of matter—hydrogen—is converted into helium by a succession of nuclear fusion reactions, and a vast amount of energy is released.

It is natural that the idea of producing similar reactions here on earth, in order to make use of the power from them, should have been current for many years. The problem of how to do this has now come to the forefront of nuclear energy research. Its solution will provide access to the well-nigh inexhaustible energy resources of the light elements—energy which can be released by thermonuclear fusion processes at very high temperatures, but cannot be obtained in surplus by any other known method.

From the point of view of both scientific research and practical applications, the greatest interest attaches to producing nuclear fusion in deuterium or in a mixture of deuterium and tritium. Here only the minimum temperature, relatively speaking, is required in order to obtain intense thermonuclear reactions.

The reactions in deuterium can take place in two ways, as follows:

$$d+d \begin{array}{l} \nearrow\ {}^{3}\mathrm{He}+n, \\ \searrow\ t+p. \end{array}$$

The two branches of the reaction have almost equal probability. The energy released is 3·3 MeV for the reaction giving a neutron and 4·0 MeV for that giving a proton.

Figure 1 shows the total cross-section for the *d-d* reaction as a function of the deuteron energy W_d (in the co-ordinate system where one deuteron is at rest). When $W_d \leqq 1{\cdot}5\times10^5$ eV the variation of this cross-section can be expressed with sufficient accuracy by the formula

$$\sigma = (2{\cdot}4\times10^{-19}/W_d)\exp(-1{\cdot}4\times10^3/W_d^{\frac{1}{3}});\ \text{cm}^2,\ W_d \text{ in eV.} \qquad \text{.........}(1.1)$$

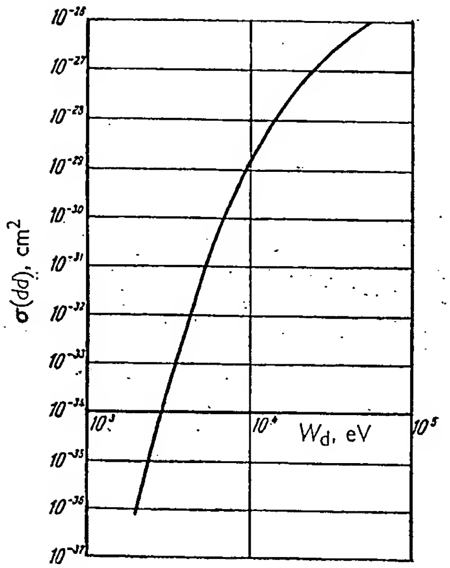

FIG. 1. Dependence of the total *d-d* reaction cross-section on deuteron energy

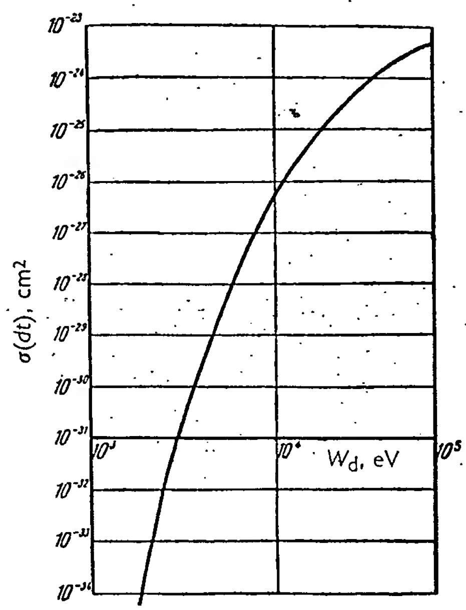

FIG. 2. Dependence of the *d-t* reaction cross-section on deuteron energy

In a mixture of deuterium and tritium, the reaction

$$d+t \rightarrow {}^4\text{He}+n$$

takes place, liberating 17·6 MeV of energy; 80% of this energy, i.e. about 14·1 MeV, is acquired by the neutron. The cross-section as a function of deuteron energy (the tritium nucleus is assumed to be at rest) is shown in Fig. 2. The cross-section for this reaction is given approximately by the formula

$$\sigma = (6\times10^{-17}/W_d)\left[1+\frac{(W_d-10^5)^2}{3\times10^{10}}\right]^{-1}\exp\left(\frac{-1{\cdot}5\times10^3}{W_d^{\frac{1}{3}}}\right);\ \text{cm}^2,\ W_d \text{ in eV.} \qquad \text{.........}(1.2)$$

This is in good agreement with experimental data for energies below about 1 MeV. When $W_d \leqq 10^5$ eV the *d-t* reaction cross-section is about a hundred times greater than the total *d-d* reaction cross-section. This is because the *d-t* reaction involves a resonance process.

ction for the d-d reaction as a function o-ordinate system where one deuteron the variation of this cross-section can y by the formula

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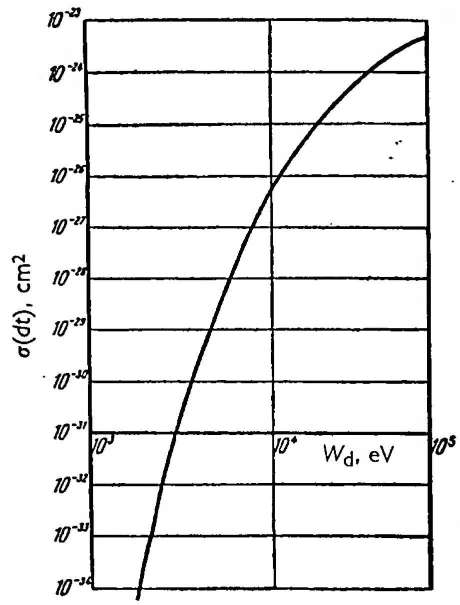

FIG. 2. Dependence of the d-t reaction cross-section on deuteron energy

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xperimental data for energies below he d-t reaction cross-section is about a tal d-d reaction cross-section. This is resonance process.

Given the cross-section as a function of particle energy, it is possible to calculate the thermonuclear reaction rate in matter. The number of nuclear reactions taking place in 1 cm³ during 1 sec is given by the expression

$$g = n_1 n_2 \overline{v\sigma}. \qquad \ldots\ldots\ldots(1.3)$$

Here n_1 and n_2 are the numbers of nuclei per cm³ (number density) of the two reacting species, and $\overline{v\sigma}$ is the product of the relative velocity of the nuclei and the reaction cross-section averaged over the velocity distribution of the nuclei. In calculating the reaction rate in pure deuterium the product $n_1 n_2$ is replaced by $n^2/2$, where n is the number density of deuterium nuclei.

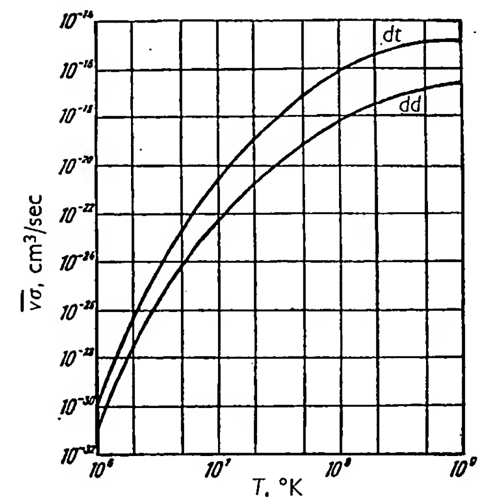

FIG. 3

Mean $v\sigma$ values (cm³ sec⁻¹) for d-d and d-t reactions when the distribution of particle energy in the plasma is maxwellian

Where the value of T is fixed† (i.e. where there is a given value for the mean kinetic energy of the random motion of the particles) the quantity $\overline{v\sigma}$ is still not determined uniquely because it is very sensitive to the particle velocity distribution. Where temperatures are not too high ($T \leq 10^8$), the marked dependence of the cross-section on the relative velocity v results in the major part of the thermonuclear reactions being due to collisions between particles whose energy is several times greater than the mean value of the thermal energy $3/2kT$. Thus the reaction rate depends markedly on the detailed shape of that part of the energy spectrum made up by the small proportion of particles with an energy considerably in excess of the mean value. It may be assumed that where 'randomising' processes take place rapidly compared to all other processes, a Maxwellian velocity distribution will be established. Figure 3 shows values of $\overline{v\sigma}$ for the d-d and d-t reactions in the temperature range 10^6 to 10^9 °K, i.e. from 10^2 to 10^5 eV, for Maxwellian velocity distributions. When the temperatures do not exceed 10^8 °K (10^4 eV), use can also be made of the following formulae to determine the reaction rate:

† Henceforth T will be used to signify temperature measured in °K. Temperature in electron-volts will be designated by θ. As is familiar, $T = 11{,}610\,\theta$.

$$g_{dd} = 7.5\times 10^{-10}(n^2/T^{\frac{2}{3}}) \exp(-4{\cdot}25\times 10^3/T^{\frac{1}{3}}) \text{ reactions cm}^{-3}\text{ sec}^{-1}; \qquad \ldots\ldots\ldots(1.4a)$$

$$g_{dt} = 1{\cdot}6\times 10^{-7}(n_1 n_2/T^{\frac{2}{3}}) \exp(-4{\cdot}52\times 10^3/T^{\frac{1}{3}}) \text{ reactions cm}^{-3}\text{ sec}^{-1}. \qquad \ldots\ldots\ldots(1.4b)$$

However, the assumption of a Maxwellian velocity distribution is not by any means justified in all cases of interest to us. When a heating pulse of short duration takes place in a low density plasma, it may well be that there is insufficient time to establish a Maxwellian velocity distribution. This may mean that, although the random motion of the particles can be defined by a specific temperature (meaning by this a quantity proportional to the mean particle energy), the proportion of particles which populate the very high energy part of the energy spectrum is nevertheless negligible. In such a situation the reaction rate is reduced significantly. Figure 4 shows how the *d-d* reaction rate compares for two different velocity distributions, the temperatures being the same: g_1 corresponds to a Maxwellian distribution, g_2 to the case where all the particles have the same energy. Admittedly the second of these distributions, here selected for purposes of comparison, is not a realistic one; nevertheless the comparative values of g_1 and g_2 illustrate how greatly the shape of the energy spectrum influences the reaction rate. We see that for a temperature of about 10^6 °K a significant departure from a Maxwellian distribution can diminish the nuclear reaction rate by several orders of magnitude. As T increases, the ratio g_1/g_2 decreases until at $T = 10^8$ °K it approaches unity. This change in g_1/g_2 is qualitatively quite understandable: when the energy is high, σ is not nearly so strongly dependent on W_d.

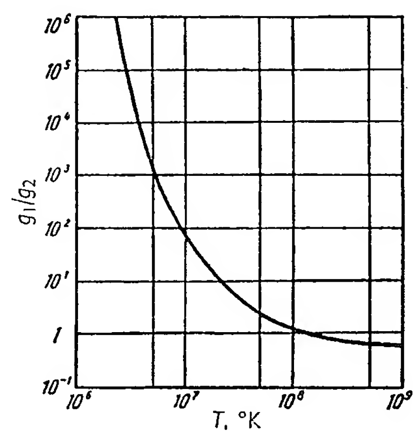

FIG. 4

Ratio of the *d-d* reaction rates for two different particle velocity distributions

From the above data on thermonuclear reaction rates, it follows that the experimentalist can hope to detect the first signs of nuclear reactions in heated matter only when the temperature reaches something like a million degrees. If thermonuclear processes are to be of any practical value for energy production, a considerably higher temperature—hundreds of millions of degrees—is required.

$4{\cdot}25\times10^3/T^{\frac{1}{3}}$) reactions $cm^{-3}\ sec^{-1}$;
.........(1.4a)

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At temperatures of a million degrees or more, matter exists as a plasma with a high degree of ionisation† (the degree of ionisation approaches 100% in stationary conditions). Only a fairly small amount of energy has to be concentrated in a plasma in order that its temperature should be high enough to ensure a high thermonuclear reaction rate. For instance, in hydrogen plasma with number density $n = 10^{15}\ cm^{-3}$, the energy required for $T = 10^8$ °K amounts to only 4 joules/cm^3. If there were a method of heating plasma by which all thermal losses could be eliminated in practice, then a small power source could be used to produce a large thermonuclear yield. However, the main difficulty lies precisely in reducing the thermal losses, which rise extremely rapidly as the temperature is raised. In the absence of magnetic fields, the coefficient of thermal conductivity of fully ionised plasma is proportional to $T^{\frac{5}{2}}$, and therefore the thermal conduction losses increase as $T^{\frac{7}{2}}$.

An idea of the sort of values involved in the heating process, under conditions of unrestricted thermal conduction, can be obtained from an actual example. A sphere with a heat source at the centre is an ideal heating configuration. A simple calculation gives the following relationship between the total thermal flux and the temperature of a small central heat-source in a large conducting sphere:

$$Q = (8\pi/7)\alpha_T r_1 T^{\frac{7}{2}}. \qquad ....(1.5)$$

Here Q is the heat evolved per second within a region of radius r_1, T is the temperature at r_1 and α_T is the numerical multiplier in the formula for the coefficient of thermal conductivity

$$\sigma_T = \alpha_T T^{\frac{5}{2}}. \qquad ....(1.6)$$

In the c.g.s. system the value of α_T is about 10^{-6}.‡ If we take $T = 10^6$ and $r_1 = 1$ cm we find that Q is about 4×10^5 kW. The example is instructive in so far as it illustrates the scale of the difficulties that have yet to be overcome before we can generate intense thermonuclear reactions with steady-state heating.

To solve the problem, a method is needed which makes it possible either to reduce the thermal conductivity by many orders of magnitude or to separate the plasma from walls and suspend it in a vacuum.

Let us suppose that a method has been found which eliminates thermal conduction from the plasma. The energy losses will now be caused solely by radiation. As will be explained later, what is wanted in practice is a very high temperature plasma with a number density not exceeding about $10^{15}\ cm^{-3}$. Plasma as rarefied as this is very transparent to short-wave-

† A plasma is a gas in which the proportion of atoms ionised is sufficiently large for the motions of the resulting electrons and positive ions to be dominated by their collective electromagnetic interactions.

‡ Strictly speaking, α_T is not a constant: it depends both on the number density and on the temperature. However, over the range of values of n and T of interest to us, this dependence of α_T is only of a weak logarithmic character.

length electromagnetic radiation, in particular to those wavelengths corresponding to photon energies of about kT_e at these very high temperatures. Consequently the energy radiated by the plasma is many orders of magnitude less than for a black body at the same temperature. Nevertheless, the radiation loss from a hot plasma can still be very considerable.

In order to determine the magnitude of this loss the first thing that must be done is to establish what processes can be a source of electromagnetic radiation. The greater part of the electromagnetic radiation from wholly ionised high-temperature plasma is bremsstrahlung; that is, radiation due to the motion of the free electrons in the Coulomb fields of the nuclei. This radiation has the same physical origin as the X-rays in the continuous spectrum from an ordinary Röntgen tube, where the anode of the tube is bombarded by a stream of fast electrons. The quantum-mechanical theory of bremsstrahling of non-relativistic electrons was derived by Sommerfeld. Its predictions are in agreement with the experimental data obtained from continuous spectra of X-rays. According to the theory, when a fast electron moves through matter it radiates energy at a rate equal to

$$-dW_e/dt = 1{\cdot}5\times 10^{-25} n Z^2 W_e^{\frac{1}{2}} \text{ ergs sec}^{-1}. \qquad \text{.........}(1.7)$$

In this expression n is the number density of atomic nuclei, Z is their atomic number and W_e is the kinetic energy of the electron in electron-volts. The intensity of bremsstrahlung from the plasma is obtained by integrating equation (*1.7*) over the electron energy distribution. With a Maxwellian distribution, the total energy radiated by unit volume of plasma per second is calculated to be

$$Q_{\text{rad}} = 1{\cdot}6\times 10^{-27} n_e n_i Z^2 T_e^{\frac{1}{2}} \text{ ergs sec}^{-1}, \qquad \text{.........}(1.8)$$

where n_e and n_i are the number densities (cm^{-3}) of electrons and ions respectively, and T_e is the electron temperature. For the frequency range ν to $\nu+d\nu$ the power radiated is equal to

$$f(\nu)\, d\nu = 6{\cdot}8\times 10^{-38} n_e n_i Z^2 T_e^{-\frac{1}{2}} \phi\left(\frac{h\nu}{kT_e}\right) \exp\left(-\frac{h\nu}{kT_e}\right) d\nu. \qquad \text{.........}(1.9)$$

The variation of the numerical factor ϕ with $(h\nu/kT_e)$ is shown in Fig. 5.

Equation (*1.8*) for the bremsstrahlung intensity is accurate enough when T_e is not too high, so that the electrons can be considered as non-relativistic. However, when relativistic electron temperatures are reached (i.e. when T_e exceeds about 10^9 °K), the intensity of the radiation caused by interactions between electrons and the Coulomb field of the nuclei rises more rapidly with T_e than indicated by formula (*1.8*). Furthermore, at relativistic speeds collisions of electrons with other electrons also give rise to intense bremsstrahlung; thus the total radiation loss is still further enhanced.

Figure 6 shows the ratio of the actual bremsstrahlung intensity to the

n particular to those wavelengths corre- .bout kT_e at these very high tempera- diated by the plasma is many orders of ɔdy at the same temperature. Neverthe- plasma can still be very considerable. itude of this loss the first thing that must ısses can be a source of electromagnetic electromagnetic radiation from wholly s bremsstrahlung; that is, radiation due ıs in the Coulomb fields of the nuclei. al origin as the X-rays in the continuous ;en tube, where the anode of the tube is ctrons. The quantum-mechanical theory ic electrons was derived by Sommerfeld. ith the experimental data obtained from ιccording to the theory, when a fast adiates energy at a rate equal to

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actual bremsstrahlung intensity to the

value determined from equation (*1.8*), for a broad range of electron temperatures. We see that this ratio starts to diverge appreciably from unity at $T_e \simeq 5 \times 10^8$ °K. When temperatures and plasma densities are high, energy losses due to bremsstrahlung become very large. Thus, for example, at $T_e \simeq 10^9$ °K and $n \simeq 10^{15}$ cm^{-3} the power radiated by 1 m^3 of hydrogen plasma is equal to 7×10^3 kW.

It should be noted that even comparatively small concentrations of heavy impurity matter in high temperature hydrogen plasma can considerably increase the bremsstrahlung losses. For example, if hydrogen plasma is contami-

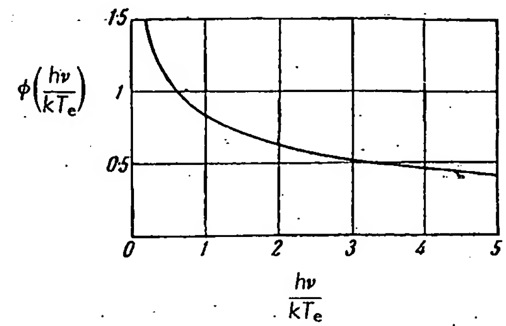


FIG. 5. The function $\phi(k\nu/kT_e)$ of equation (*1.9*)

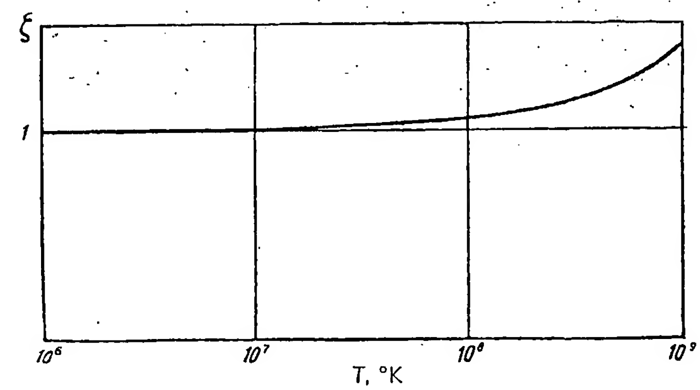


FIG. 6. The ratio ζ of the total energy radiated as bremsstrahlung to that given by equation (*1.8*)

nated with 0·1% of copper nuclei, then this contamination will nearly double the bremsstrahlung intensity.

When the electron temperatures are comparatively low ($T_e < 10^8$), the enhancement of the radiation from a hydrogen plasma by contamination is even greater, because the processes of radiative recombination and line radiation become very intense when conditions are insufficient to strip all the atoms of their bound electrons. We shall return to this topic in the next chapter.

Bremsstrahlung of fast electrons causes an unavoidable loss of energy from plasma heated to high temperature. No known method of thermally insulating hot plasma can have any noticeable effect on this loss. A thermo-

nuclear generator can, therefore, produce surplus energy only when the total energy produced in fusion reactions exceeds these radiation losses. The nuclear energy produced and the radiation losses depend alike on the plasma number density (both are proportional to n^2), and consequently

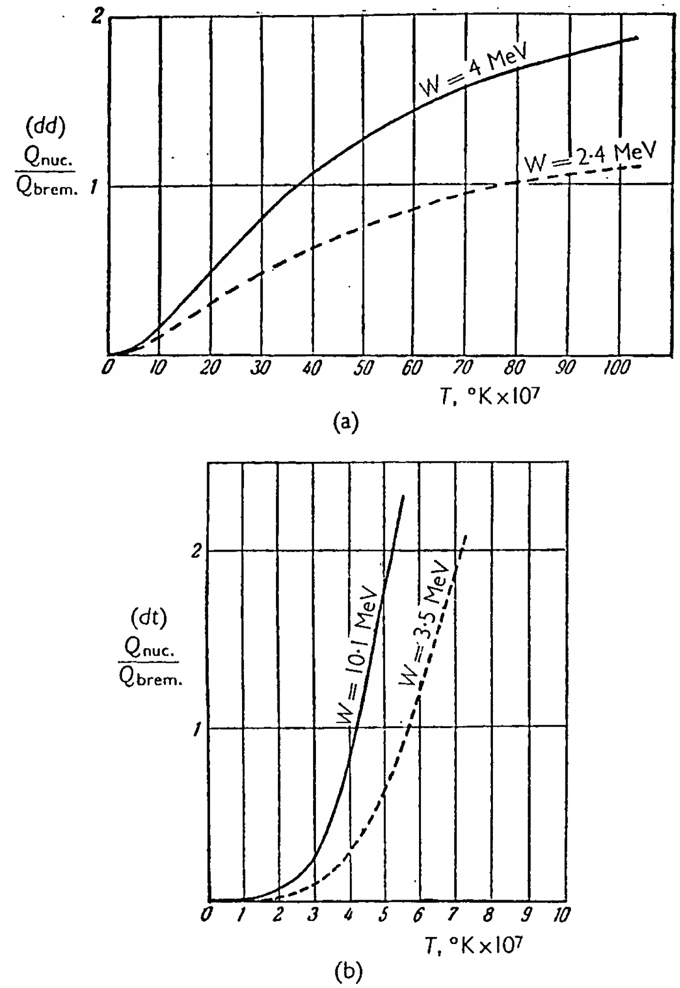


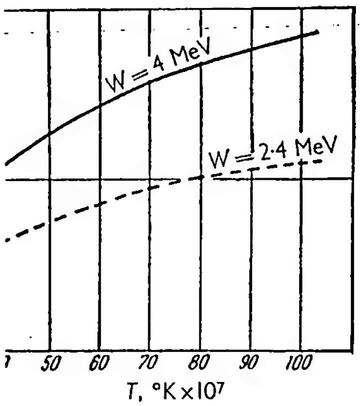
FIG. 7. Ratio of the energy released by thermonuclear reactions to that lost by bremsstrahlung:

(a) for the *d-d* reaction
(b) for the *d-t* reaction

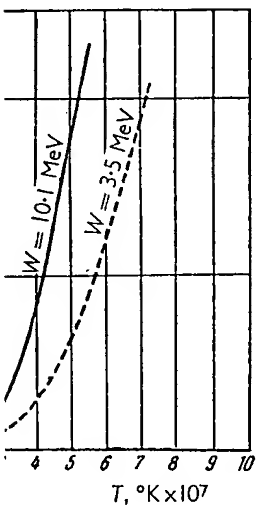
their ratio for a given nuclear fuel is solely a function of the plasma temperature.

The curves reproduced in Figs. 7a and 7b show this ratio as a function of plasma temperature T: (a) for pure deuterium, and (b) for a 50% mixture

produce surplus energy only when the
eactions exceeds these radiation losses.
the radiation losses depend alike on the
proportional to n^2), and consequently



(a)



(b)

:eleased by thermonuclear reactions
by bremsstrahlung:

the *d-d* reaction
the *d-t* reaction

uel is solely a function of the plasma

. 7a and 7b show this ratio as a function
ıre deuterium, and (b) for a 50% mixture

of deuterium and tritium. The dotted curves do not take into account all the energy released by the fusion reactions, but only that part of it which appears as kinetic energy of the charged reaction products, i.e. that part of the energy which can be directly deposited as heat in the plasma and which, in principle, can be converted with high efficiency into electrical energy. That part of the energy carried away by the neutrons (to which has been added a neutron binding energy† of 8 MeV which is assumed to be released when the neutron is finally captured) is deposited in some moderating medium outside the volume occupied by the plasma, and can be utilised in the form of electrical energy with a normal thermal efficiency of only about 0·3. Allowance for this second portion of energy (adopting 0·3 for the efficiency) raises the energy output by 65% (from 2·4 to 4 MeV) in pure deuterium and by 180% (from 3·5 to 10·1 MeV) in a mixture of deuterium and tritium. The corresponding curves are shown in Figs. 7a and 7b by unbroken lines. It should be noted that the graphs of Fig. 7 were obtained by taking the ion temperature T_i as equal to the electron temperature T_e. It may be that in practice this equality cannot be maintained. In particular, if the entire heating flux were to go directly into the positive ions, and losses were due solely to bremsstrahlung, then T_e would be less than T_i: indeed the ratio T_e/T_i would be far from unity.

We can see from Figs. 7a and 7b that a system generating thermonuclear reactions can serve as a nuclear power station only if the plasma temperature exceeds some critical temperature T_c which amounts to about $3{\cdot}5 \times 10^8$ °K for deuterium, and to about 4×10^7 °K for a 50% mixture of deuterium and tritium.‡ These critical temperatures are calculated assuming that optimum use is made of the thermonuclear energy released. If one counts only that part of the energy carried by the charged reaction products, then the calculated values of T_c are correspondingly higher.

Bremsstrahlung of fast electrons accounts entirely for the radiation from high-temperature hydrogen plasma in the high-frequency region ($h\nu \simeq kT_e$). In the low-frequency region other physical processes also can contribute to the radiation losses. In particular, at very high temperatures (beginning at about 10^8 °K) losses due to so-called betatron radiation (also called 'magnetic bremsstrahlung', 'cyclotron radiation' and 'synchrotron radiation') can become large. We shall consider this type of loss later when analysing the properties of proposed thermonuclear generators.

§ **1.2** The fundamental and very difficult problem requiring solution, if intense controlled thermonuclear reactions are to be realised, is how to insulate the very high-temperature plasma from the surrounding walls of

† The neutron binding energy added is the energy released when neutrons are captured by atomic nuclei. For most stable nuclei this energy varies between 7 and 11 MeV, and has an average value of about 8 MeV over the whole periodic table.

‡ If one assumes partial utilisation of the energy lost as bremsstrahlung, the values of T_c go down. They drop further if, when calculating the energy yield for *d-d* reactions, one allows for the additional sources of nuclear energy provided by the formation of tritium (see below).

item U2 an PTo 892.

IEEE★USA

POSITION

Fusion Energy Research and Development

Approved by the IEEE-USA Board of Directors (June 1999)

The Institute of Electrical and Electronics Engineers - United States of America (IEEE-USA) endorses research and development in fusion power aimed at deriving the knowledge base to exploit fusion as a virtually inexhaustible, environmentally attractive and economical power source for base load electrical power generation.

IEEE-USA supports fusion research and development as a component of a broad program of research and development in energy technologies, targeted at reducing environmental impacts of increasing worldwide energy use while assuring an adequate, reliable and economical supply of electrical energy. We recommend increased funding for R&D in energy technologies, generally to provide a diverse set of options for efficient end-use and acceptable electricity generation and transmission in the near- and long-terms. Our vision emphasizes energy efficiency and conservation, and a diversification of energy sources including solar and renewable energy, advanced nuclear fission technology, and fusion in order to reduce the need for burning fossil fuels.

With the energy situations in the U.S., Europe, Japan, Russia and developing nations being quite different; with some like the U.S. having large energy reserves and others projecting shortages in the next 100 years; and in light of the global nature of possible climate change, IEEE-USA believes that it is important for the U.S. to address the worldwide situation and to play a leadership role in the worldwide fusion program. The U.S. should position itself to become a supplier of attractive fusion power systems when needed. Especially important is research and development targeted at increasing the attractiveness of the fusion power system from the safety, environmental and economic perspectives.

IEEE-USA supports a fusion program that includes:

1. development of fusion science, technology, magnetic confinement innovations, and inertial fusion energy as the central themes of the domestic program and a theme of the international collaboration program;
2. study of burning plasma science, including both experiments on relevant existing domestic and international machines and participation on an international burning plasma facility;
3. development of fusion technology including enabling technologies, superconducting magnets and advanced materials, especially low activation materials;
4. advancement of plasma and fusion science and engineering in pursuit of

national science and technology goals; and
5. continuation of broad areas of international cooperation in performing fusion power research but stressing the importance of having a strong and stable domestic program to maintain essential national physics and engineering capabilities and to assure international competitiveness.

The statement was developed by the Energy Policy Committee of The Institute of Electrical and Electronic Engineers - United States of America (IEEE-USA) and represents the considered judgment of a group of U.S. IEEE members with expertise in the subject field. IEEE-USA promotes the careers and public policy interests of the 225,000 electrical, electronics and computer engineers who are U.S. members of the IEEE.

BACKGROUND

Fusion Energy Overview

In its most achievable form, fusion energy comes from the conversion of hydrogen into helium, with the release of energetic helium nuclei and neutrons. A reduction in the total mass of the reacting particles releases energy, in accord with Einstein's theory of relativity.

Due to the electrostatic repulsion of the positively-charged reacting nuclei, low energy nuclei do not get close enough to stick together (i.e.,.fuse); hence, the probability of a fusion reaction is strongly dependent on the energies of the reacting nuclei -- requiring "temperatures" in excess of roughly 100 million degrees Centigrade to have a significant population of sufficiently energetic nuclei. At such temperatures the fuel is a "plasma" in which the electrons are not bound to the positively-charged nuclei. The fusion burn of the plasma is sustained if confinement times and particle densities are adequately large (the so-called Lawson criterion requiring that their product exceed roughly 1014 seconds/cm3).

The potential advantages of fusion power include:

- universally available and virtually inexhaustible fuel;
- negligible atmospheric emissions, in contrast to the C02 and acid emission from burning fossil fuels;
- limited impacts on ecological and geophysical processes; and
- radiological hazards and proliferation risks significantly less than with nuclear fission power.

The potential disadvantages of fusion power include:

- a long development period prior to a demonstration fusion power plant;
- relatively large unit size of fusion power plants (~1000 MW with present concepts and possibly ~500 MW with more advanced concepts);
- large module size for magnetic fusion program development steps, demanding a development program that includes large and expensive facilities; both the magnetic and inertial fusion programs are exploring the possibility of smaller development steps; and

- radioactivity, albeit with significantly less long-term activity and shorter half-lives than with fission power.

The thermonuclear fusion energy program is being conducted along two parallel paths: magnetic and inertial fusion energy.

- Magnetic confinement fusion (MCF) uses strong magnetic fields to confine the reacting particles for periods of times exceeding seconds. MCF is an unclassified program benefiting from extensive international collaboration.
- Inertial confinement fusion (ICF) uses focused high-power sources (lasers and particle beams) to compress and heat small target pellets and confines the reacting mixture by its own inertia for very brief times (about a billionth of a second). Aspects of DOE's ICF program relating to nuclear weapons are classified, but much of ICF relating to inertial fusion energy was declassified by DOE in December 1993.

Highlights of Fusion Research

Controlled fusion research has made significant progress since its inception in the early 1950's. For example, the equivalent gain (ratio of fusion power out to heating power in) of magnetic confinement fusion experiments has risen from 1/1,000,000 twenty years ago to nearly unity (i.e., one) in the United States' Tokamak Fusion Test Reactor and in the Joint European Torus. In the inertial confinement fusion program, experiments in a classified program called Centurion/Halite have provided evidence that ICF in the laboratory is technically feasible.

Recent highlights of the U.S. magnetic fusion energy program include:

- the production of more than 10 million watts of fusion power in the U.S.'s Tokamak Fusion Test Reactor (TFTR) and Europe's Joint European Torus (JET);
- achievement of promising regimes of improved plasma confinement and stability in base program tokamaks; and
- successful completion of the Final Design Report of the International Thermonuclear Experimental Reactor (ITER), via a partnership between the governments of Japan, the Russian Federation, the European Community, and the United States.

Recent highlights of the U.S. inertial fusion energy program have been:

- improved pellet compression using innovative techniques to smooth the incident energetic compression beam;
- declassification of significant parts of the ICF program, which has led to increased openness, participation by universities and industry, and increased communication with the international ICF program participants;
- demonstration that an energy of five to 10 MegaJoules on the ICF target is adequate to achieve high gain (fusion yield many times larger than the required driver energy);
- start of construction for the inertial confinement fusion National Ignition Facility (NIF), which is targeted at fusion ignition and energy gain in the laboratory.

IEEE-USA's Fusion Energy Principles

Fusion policy recommendations should be developed in the context of the following principles:

- The U.S. must invest in energy science and technology research and development to ensure that the U.S. industry acquires the expertise to become a major supplier of efficient end-use equipment and efficient, reliable and environmentally attractive electricity generation and transmission systems in the future.

- Consistent with the 1992 recommendations of the Secretary of Energy Advisory Board's Task Force on Priorities, "every effort should be made to secure a future Energy Research budgetary profile that is more in keeping with the outstanding scientific opportunities before the nation and the traditional role of the DOE as a major source of support for fundamental science and engineering research."

- Energy policy should be based on a long-range national energy plan, and should achieve a prudent balance between international collaboration (for U.S. cost reduction) and a strong domestic program (to ensure national competence and competitiveness).

- Fusion should be developed as an element within a portfolio of long-term electrical energy generation technologies because of fusion's potential as an inexhaustible and environmentally attractive energy source.

- Due to the long-term nature of the fusion R&D program and fusion energy's significant environmental and national security advantages, stable government commitment to the long-term development of fusion power is essential to exploit the international fusion advances and to lead in strategically important areas.

- U.S. industry should be involved in appropriate roles such that U.S. industry will have the skills to compete in the international market for providing fusion reactors in the future.

- While international collaboration is needed for fusion energy and technology projects, a strong, complementary domestic program is necessary to assure the U.S.'s ability to be a strong international partner and to maintain the U.S.'s competitiveness in the design and construction of future fusion power systems.

- The national laboratories should transfer technology, but will have strong roles for the foreseeable future.

- The U.S. should assure funding sources for university-based research in both magnetic and inertial fusion energy, both to provide the intellectual stimulus, objective criticism, and innovative thinking that universities foster and to train future scientists and engineers. A recent National Research Council Research Briefing on Contemporary Problems in Plasma Science highlighted many exciting opportunities for university research, including the innovative use of fusion facilities. Many of these opportunities are not being exploited because funding sources for basic plasma sciences are extraordinarily limited.

IEEE-USA's Fusion Energy Recommendations

(1) Because energy is perceived to be plentiful in the U.S. in the near-term, because development of an attractive fusion reactor will take decades, and because the market for fusion will likely arise only when the demand from the developing nations has risen significantly and when concerns about climate change are sufficient to justify demonstration of clean electric power production from non-fossil sources, the main focus of the U.S. domestic fusion program should be the development of the knowledge base for designing an environmentally and economically attractive power source. Due to the present uncertainties about the concepts, both magnetic and inertial fusion approaches should be pursued. The present barriers to the design of an attractive fusion configuration include both science and technology, so programs in fusion science, fusion technology and concept innovation are required. Both domestic and international facilities can contribute to this pursuit. Therefore, IEEE-USA makes the following statement.

IEEE-USA supports a fusion program that includes development of fusion science, technology, magnetic confinement innovations and inertial fusion energy as the central themes of the domestic program and a theme of the international collaboration program.

(2) In the magnetic fusion program, the science and technology of burning plasmas are key elements in the design of a fusion reactor and are a major focus of the world magnetic fusion program. The science elements include the self-heating of the plasma by the fusion products, the effects of the feedback between the self-heated plasma and the transport and stability of the system, and the physics of plasmas at the scale of a reactor. Limited studies of the physics of burning plasmas can be conducted on existing machines; the Joint European Torus is the only existing facility capable of utilizing the most promising fusion fuels, deuterium and tritium; and several existing domestic and international tokamaks can study some of the physics of energetic particle confinement and stability. However, a more complete study of the physics of burning plasmas and the integration of physics and technology would demand a facility that cannot be afforded within the U.S. domestic program, thereby motivating international collaborations either on an integrated device or on a set of smaller devices focused on more restricted sets of objectives. Therefore, IEEE-USA makes the following statement.

IEEE-USA supports a magnetic fusion program that includes study of burning plasma science, including both experiments on relevant existing domestic and international machines and participation in an international burning plasma facility.

(3) Technological barriers must be overcome before an attractive fusion reactor can be designed; this is true in both the magnetic and inertial fusion programs. In the magnetic program, superconducting magnets must be used to reduce the recirculating power; heating and current drive systems must be improved to support more precise control of the plasma profiles; low activation structural materials must be developed to reduce the level of radioactive waste; blanket systems must be developed to convert the neutron power to a more usable form; and plasma-facing materials must be improved to handle the exhaust power. In the inertial program, "drivers" such as particle beams and advanced lasers must be developed to provide repetitive compressions of the targets; plasma-facing materials and configurations must be improved to handle the exhaust power; and low activation materials would reduce the radioactive waste. Therefore, IEEE-USA makes the following statement.

IEEE-USA supports a fusion program that includes development of fusion technologies including enabling technology, superconducting magnets and

advanced materials, especially low activation materials.

(4) The tools for optimization of the "core" of a magnetic fusion plasma are based on understanding of the transport of energy and particles in plasmas from one electron volt (about 10,000 degrees Centigrade) to 20,000 electron volts (about 20,000,000 degrees Centigrade), of the stability of magnetically-contained plasmas, of interactions of such plasmas with radio waves and particle beams, and of plasma interactions with solid material walls. Inertial confinement fusion tools involve understanding of transport, stability and interactions between very high-density plasmas (up to around 1000 times solid density) and high-intensity laser beams and intense high-energy particle beams. These scientific topics are not addressed adequately in any other governmental program; hence, the magnetic and inertial fusion programs should be the "stewards" of this branch of science. Therefore, IEEE-USA makes the following statement.

IEEE-USA supports a fusion program that includes advancement of plasma and fusion science and engineering in pursuit of national science and technology goals.

(5) Success of international collaboration demands that the partners share the goal, benefit from the success of joint programs, and bring value to the collaboration. To be an effective international partner, the U.S. must support in a stable manner a strong domestic fusion science and technology program to provide strong capabilities to participate effectively in international collaborations and to enable the U.S. to be competitive. Therefore, IEEE-USA makes the following statement.

IEEE-USA supports a fusion program that includes continuation of broad areas of international cooperation in performing fusion power research but stressing the importance of having a strong and stable domestic program to maintain essential national physics and engineering capabilities and to assure international competitiveness.

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